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Geothermal energy technology and current status: an overview

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Abstract

Geothermal energy is the energy contained as heat in the Earth's interior. This overview describes the internal structure of the Earth together with the heat transfer mechanisms inside mantle and crust. It also shows the location of geothermal fields on specific areas of the Earth. The Earth's heat flow and geothermal gradient are defined, as well as the types of geothermal fields, the geologic environment of geothermal energy, and the methods of exploration for geothermal resources including drilling and resource assessment.

Geothermal energy, as natural steam and hot water, has been exploited for decades to generate electricity, and both in space heating and industrial processes. The geothermal electrical installed capacity in the world is 7974 MW_e (year 2000), and the electrical energy generated is 49.3 billion kWh/year, representing 0.3 % of the world total electrical energy which was 15,342 billion kWh in 2000. In developing countries, where total installed electrical power is still low, geothermal energy can play a significant role: in the Philippines 21% of electricity comes from geothermal steam, 20% in El Salvador, 17% in Nicaragua, 10% in Costa Rica and 8% in Kenya. Electricity is produced with an efficiency of 10–17%. The geothermal kWh is generally cost-competitive with conventional sources of energy, in the range 2–10 UScents/kWh, and the geothermal electrical capacity installed in the world (1998) was 1/5 of that from biomass, but comparable with that from wind sources.

The thermal capacity in non-electrical uses (greenhouses, aquaculture, district heating, industrial processes) is 15,14 MW_t (year 2000). Financial investments in geothermal electrical and non-electrical uses world-wide in the period 1973–1992 were estimated at about US$22,000 million. Present technology makes it possible to control the environmental impact of geothermal exploitation, and an effective and easily implemented policy to encourage geothermal

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energy development, and the abatement of carbon dioxide emissions would take advantage from the imposition of a carbon tax. The future use of geothermal energy from advanced technologies such as the exploitation of hot dry rock/hot wet rock systems, magma bodies and geopressured reservoirs, is briefly discussed. While the viability of hot dry rock technology has been proven, research and development are still necessary for the other two sources. A brief discussion on training of specialists, geothermal literature, on-line information, and geothermal associations concludes the review.

Keywords: Geothermal energy; Geothermal resources; Geothermal technology; Geothermal economics

Contents

1. Introduction

Geothermal energy is the energy contained as heat in the Earth's interior. The origin of this heat is linked with the internal structure of our planet and the physical processes occurring there. Despite the fact that this heat is present in huge, practically inexhaustible quantities in the Earth's crust, not to mention the deeper parts of our planet, it is unevenly distributed, seldom concentrated, and often at depths too great to be exploited industrially.

The heat moves from the Earth's interior towards the surface where it dissipates, although this fact is generally not noticed. We are aware of its existence because the temperature of rocks increases with depth, proving that a geothermal gradient exists: this gradient averages 30°C/km of depth.

There are, however, areas of the Earth's crust which are accessible by drilling, and where the gradient is well above the average. This occurs when, not far from the surface (a few kilometres) there are magma bodies undergoing cooling, still in a fluid state or in the process of solidification, and releasing heat. In other areas, where magmatic activity does not exist, the heat accumulation is due to particular geological conditions of the crust such that the geothermal gradient reaches anomalously high values.

The extraction and utilisation of this large quantity of heat requires a carrier to transfer the heat toward accessible depths beneath the Earth's surface. Generally the heat is transferred from depth to sub-surface regions firstly by *conduction* and then by *convection*, with geothermal fluids acting as the carrier in this case. These fluids are essentially *rainwater* that has penetrated into the Earth's crust from the *recharge* areas, has been heated on contact with the hot rocks, and has accumulated in aquifers, occasionally at high pressures and temperatures (up to above 300°C). These aquifers (reservoirs) are the essential parts of most *geothermal fields*.

In most cases the reservoir is covered with impermeable rocks that prevent the hot fluids from easily reaching the surface and keep them under pressure. We can obtain industrial production of superheated steam or steam mixed with water, or hot water only, depending on the hydrogeological situation and the temperature of the rocks present (Fig. 1).

Wells are drilled into the reservoir to extract the hot fluids, and their use depends on the temperature and pressure of the fluids: generation of electricity (the most

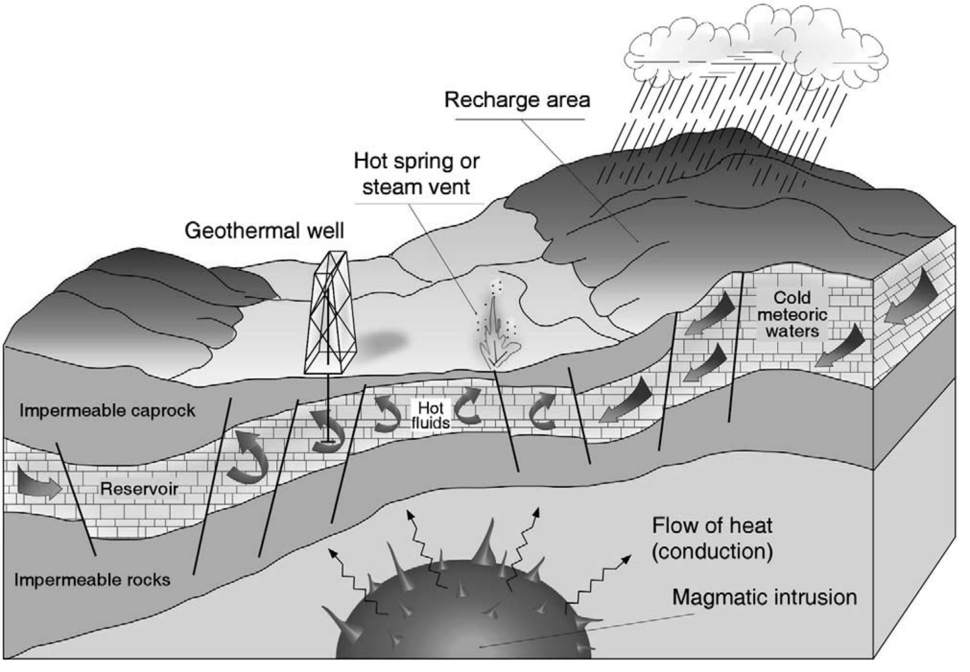


Fig. 1. A geothermal steamfield with its elements: recharge area, impermeable cover, reservoir and heat source.

important of the so-called high-temperature uses), or for space heating and industrial processes (low-temperature uses).

Geothermal fields, as opposed to hydrocarbon fields, are generally systems with a continuous circulation of heat and fluid, where fluid enters the reservoir from the recharge zones and leaves through discharge areas (hot springs, wells). During industrial exploitation fluids are recharged to the reservoir by reinjecting through wells the waste fluids from the utilisation plants. This reinjection process may compensate for at least part of the fluid extracted by production, and will to a certain limit prolong the commercial lifetime of the field. Geothermal energy is therefore to some extent a renewable energy source, hot fluid production rates tend however to be much larger than recharge rates.

2. Geological background

2.1. The Earth's structure

The Earth is formed by three concentric zones, crust, mantle and core (Fig. 2).

Crust. The Earth's crust is analogous to the skin of an apple. The thickness of the crust (7 km on average under the ocean basins, 20–65 km under the continents)

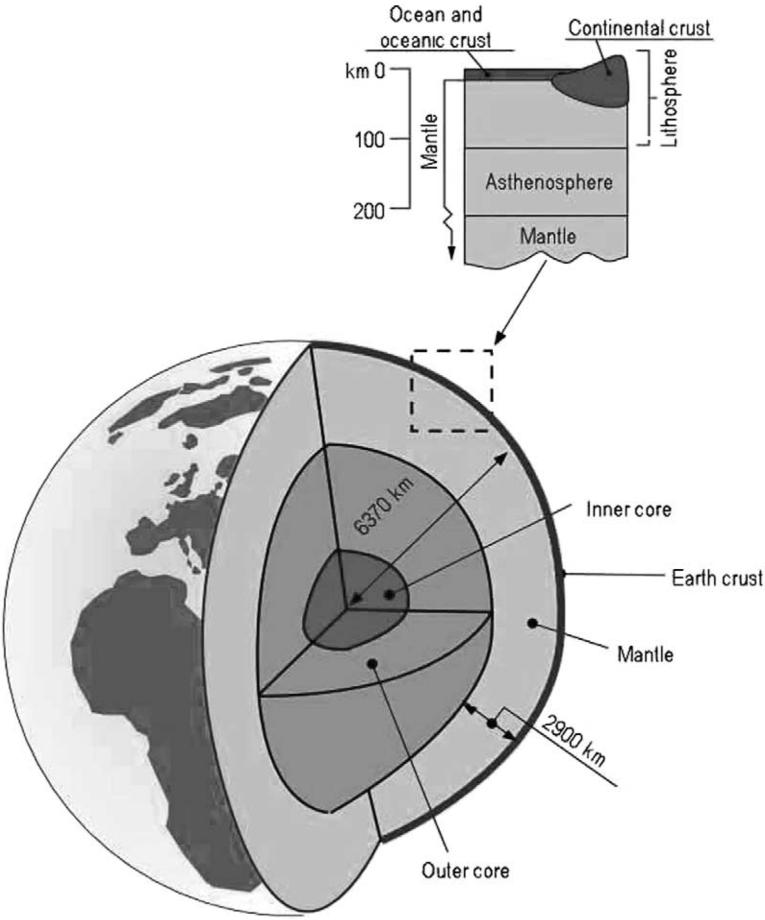


Fig. 2. The Earth's crust, mantle and core. On the top right a section through the crust and the uppermost mantle.

is insignificant compared to the rest of the Earth which has an average radius of 6370 km. Wells give us direct access only to the crust, and to depths not much beyond 10 km. Studies of seismic waves have shown that the Earth's crust is thinner beneath the oceans than beneath the continents, and that seismic waves travel faster in oceanic crust than in continental crust. In part because of this difference in velocity, it is assumed that the two types of crust are made up of different kinds of rock. The denser, oceanic crust is made of basalt, whereas the continental crust is often referred to as being largely granite.

Mantle. The mantle lies closer to the Earth's surface beneath the ocean (at a depth of 7 km), than it does beneath the continents (20–65 km). It extends from the base of the crust for about 2900 km. The most accepted hypothesis about the composition of the mantle is that it consists of ultrabasic rock (very rich in Fe and Mg) such as

peridotite, which is a heavy igneous rock made up chiefly of ferromagnesian minerals.

The Earth's crust and uppermost mantle together form the lithosphere, the outer shell of the Earth that is relatively rigid and brittle (Fig. 2). The lithosphere is split into a number of large blocks at continental scale or more, which are called lithospheric plates in the plate tectonic theory.

The lithosphere (crust and upper mantle) is about 70 km thick beneath the oceans and 100–125 km thick beneath the continents. Its lower boundary inside the mantle is marked by a particular layer, known as the low-velocity zone, in which seismic waves slow down. This zone, extending to a depth of perhaps 200 km, or more, from the surface, is called the asthenosphere. Rocks in the asthenosphere may be closer to their melting point than rocks above or below this zone.

Mantle rocks in the asthenosphere are weaker than they are in the overlying lithosphere, then the asthenosphere can deform easily by plastic flow, and convection can take place within the asthenosphere as well as within the lower mantle.

The lithosphere seems to be in continual movement, probably as a result of the underlying mantle convection, and plates of brittle lithosphere probably move easily over the asthenosphere, which may act as a lubricating layer below.

Core. The Earth's core extends from 2900 to 6370 km (the Earth's centre): its thickness, or radius, is 3470 km. The temperature in the core should be around 4000°C and the pressure at the Earth's centre 3.6 million bar (360,000 MPa).

2.2. The plate tectonic theory

The plate tectonic theory, currently accepted by most geologists, is a unifying theory that accounts for many apparently unrelated geological phenomena. According to this theory the rigid outer shell of the Earth, or lithosphere (crust and upper mantle, thickness in the range 70–100/125 km), is divided into separate blocks or plates, termed *lithospheric plates* (Fig. 3). These plates move slowly across the Earth's surface, at a speed of a few centimetres per year. As the plates comprise both continents and sea floors, the plate tectonics concept means that the continents and sea floors are moving, sliding on top of the underlying plastic asthenosphere. These plates either pull away from each other, slide past each other, or move towards each other.

The boundaries between plates are of three types (Fig. 4):

- Diverging plate boundaries (or spreading centres, or ocean ridges). These occur where two plates are moving apart, thus permitting the upwelling of magma from the asthenosphere to form new lithosphere. Most spreading centres coincide with the crest of submarine mountain ranges, called mid-oceanic ridges which rarely rise above sea level (for example, Iceland);
- Converging plate boundaries. These correspond to oceanic trenches, where two plates converge and collide so that one plate slips and sinks below the other and is eventually reabsorbed into the mantle and "destroyed" (for example, the Nazca plate in the eastern Pacific Ocean). Convergence occurs when one plate is made

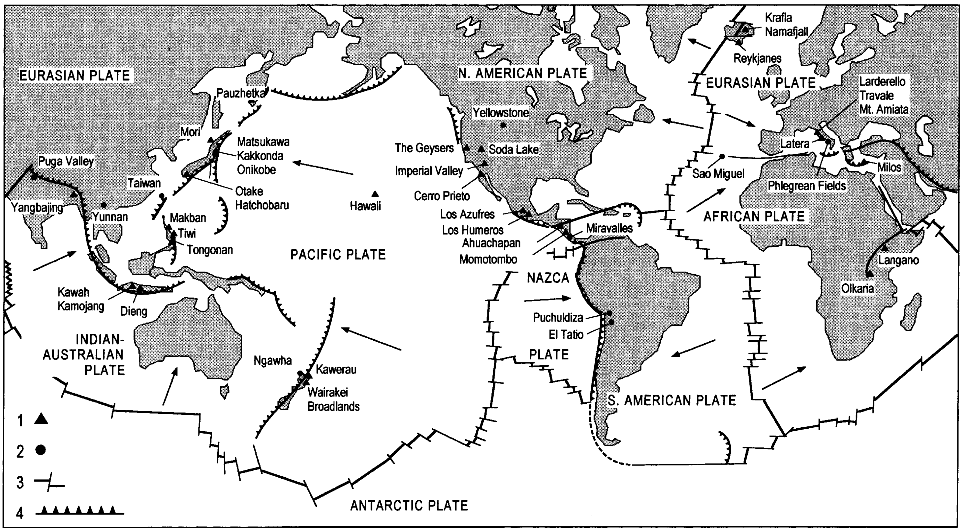


Fig. 3. World pattern of plates, oceanic ridges, oceanic trenches, subduction zones, and geothermal fields that currently generate electricity. Arrows show the direction of movement of the plates towards the subduction zones. 1) Geothermal fields under exploitation; 2) Fields not yet exploited; 3) Mid-oceanic ridges crossed by transform faults (long transversal fractures); 4) Subduction zones, where the subducting plate bends downwards and melts in the asthenosphere.

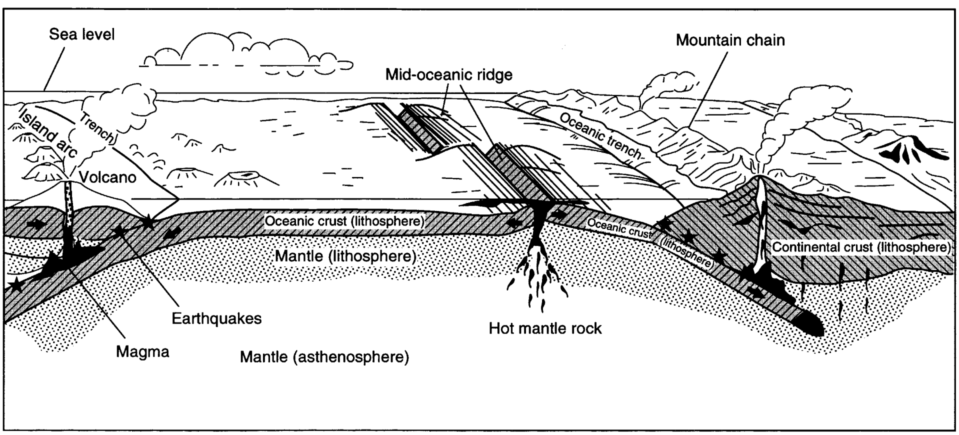


Fig. 4. The basic concept of plate tectonics. Plates of rigid lithosphere (which include the oceanic or the continental crust, and the uppermost mantle), 70-125 km thick, overlie a layer of relatively low strength called asthenosphere. Mantle material rises below diverging plate boundaries (oceanic ridges), and plate material descends into the mantle at converging plate boundaries (oceanic trenches). Source [44].

of oceanic crust and the other of continental crust. The less dense, more buoyant, continental plate will override the denser oceanic plate. The oceanic plate sinks along what is known as a subduction zone, where an oceanic plate descends into the mantle beneath an overriding plate. The entire oceanic plate becomes hotter as it descends deeper into the Earth's interior and melts down;
- Conservative plate boundaries. These are faults where two plates slide past each other, so that no lithosphere is either created or destroyed. In this case, the direction of relative motion of the two plates is parallel to the fault. Conservative plate margins occur within both the oceanic and continental lithosphere, but the most common conservative plate margins are oceanic transform faults (e.g., the San Andreas fault in California; the earthquakes along the fault are the results of plate motion).

The different types of plate boundaries were originally distinguished on the basis of their seismicity. Earthquakes commonly occur at the boundaries of plates, and only occasionally in the middle of a plate. There is a close correspondence between plate boundaries and earthquake belts.

We have already seen that plate tectonic processes are linked to mass movement in the mantle. Because such movement can only occur within materials that have the properties of fluids, this implies that the mantle shows some form of fluid behaviour.

2.3. The Earth's heat

Our ancestors were well aware that the Earth's interior was hot. The Latin poet Ovid in Book XV of his *Metamorphoses* (verses 342–343), written about 3 A.D., has the philosopher and mathematician Pitagoras (who lived 500 years before him) declare that there is a great fire in the Earth's interior, and that this fire is manifest at the surface in the form of volcanoes. The first systematic measurements of temperature underground are accredited to the British chemist Robert Boyle, well-known for his gas law. In 1671 Boyle wrote of the heat, sometimes very strong, noted in the mines of Britain, and stated that temperature increases with depth. This phenomenon was reappraised in 1846 by young William Thomson, later Lord Kelvin, one of the fathers of thermodynamics, who, in his PhD thesis at the University of Glasgow, tried to estimate the age of the Earth from the "distribution and movement of heat within it" [1]. However, it was not until 1882 that the values obtained for the geothermal gradient and the thermal conductivity of rocks were combined by Lord Kelvin (their product gives the heat flow) to obtain the heat flow in Great Britain [2].

The Earth's heat flow is the amount of heat that is released into space from the interior through a unit area in a unit of time. It is measured in milliwatt per square meter. It varies from place to place on the surface, and it has varied with time at any particular place during the history of our planet.

The Earth's heat flow originates from the primordial heat, which is the heat generated during the Earth's formation, and from the heat generated since the Earth's formation by the decay of long-lived radioactive isotopes. Although all radioactive isotopes generate heat as they decay, only isotopes that are relatively abundant and

have half-lives comparable to the age of the Earth (4.5 billion years) have been significant heat producers throughout geological time and remain so at present. Four long-lived radioactive isotopes are important heat producers: ^{40}K, ^{232}Th, ^{235}U and ^{238}U.

The average heat flow from the continental crust (granite) is 57 mW/m^2, and through the oceanic crust (basalt) is 99 mW/m^2. The Earth's average heat flow is 82 mW/m^2, and the total global output is over 4×10^{13} W [3], four times more than the present world energy consumption which is 10^{13} W [4]. Continental heat flow appears to be derived from radiogenic decay within the upper crust, together with the heat generated in the most recent magmatic episode and the heat coming from the mantle. In the oceanic crust, the concentration of radioactive isotopes is so low that radiogenic heating is negligible, and the heat flow largely derives from heat flowing from the mantle below the lithosphere.

We also know that:

- in the continental crust, the heat flow at the surface is highest in areas that have experienced magmatic or metamorphic activity more recently than 65 million years (from Cenozoic to present, 77 mW/m^2), and that heat flow decreases to a constant value of about 46 mW/m^2 in crust older than 800 million years (Precambrian).
- in the young oceanic crust ($<$65 million years, from Cenozoic to present) heat flow is higher and variable (70–170 mW/m^2) than in older oceanic crust ($>$65 million years), which has lower and more constant heat flow (about 50 mW/m^2). The heat flow decreases with the age of the oceanic crust [3].

2.3.1. Heat transfer within the Earth

The Earth's conductive heat flow is the product of the geothermal gradient and the thermal conductivity of rocks. The geothermal gradient is measured in shallow holes, while the conductivity of rocks is best measured in laboratory on samples (called cores) taken from that part of the well where the gradient was measured.

Two forms of heat transfer occur within the Earth: conduction and convection.

- *Conduction.* Conduction involves the transfer of random kinetic energy between molecules without the overall transfer of material. Moving molecules strike neighbouring molecules, causing them to vibrate faster and thus transfer heat energy. Conduction is the primary heat transfer mode in solids. Metals are very good conductors of heat, whereas most rocks are relatively poor conductors.
- *Convection.* Convection is the common heat transfer process in liquids or gases and consists of the movement of hot fluid (that is, a liquid or a gas) from one place to another. Because motion of material occurs, convection is a vastly more efficient process of heat transfer than conduction.

2.3.2. The Earth's geothermal gradient and the thermal conductivity of rocks

Studies of the thermal behaviour of the Earth imply the determination of how temperature varies with depth, and how such temperature variations may have

changed throughout geological time. However, studies of this kind are based entirely on measurements made on, or within, a few km of the Earth's surface during the last few decades.

The average gradient near the surface, say within a few km, is about 30°C/km, but values as low as about 10°C/km are found in ancient continental crust and very high values (>100°C/km) are found in areas of active volcanism. Once the gradient has been measured, it can be used to determine the rate at which heat is moving upwards through a particular part of the Earth's crust.

As the heat generally moves upwards through solid impermeable rock, the principal mechanism of heat transfer must be conduction. The amount of heat flowing by conduction through a unit area of 1 m^2 of solid rock in a given time, that is the rate of heat flow, is proportional to the geothermal gradient and to a constant of proportionality which is known as the *thermal conductivity* of rocks defined as the amount of heat conducted per second through an area of 1 m^2, when the temperature gradient is 1°C/m perpendicular to that area. The unit of thermal conductivity is the W/(m K) (watt per meter per degree kelvin, or per degree centigrade). The gradient is measured in wells with electrical (platinum-resistance) thermometers. Temperature logging is quick and relatively inexpensive. The thermal conductivity of rock samples is best measured in laboratory, as there are no reliable downhole methods.

If the gradient is expressed in°C/km and conductivity in W/(m°C), heat flow will be in mW/m^2 (milliwatt per square metre).

3. Geothermal resources

3.1. General aspects

Geothermal resources are the thermal energy that could reasonably be extracted at costs competitive with other forms of energy at some specified future time, this definition was given by Muffler and Cataldi in 1978 [5].

Geothermal resources are generally confined to areas of the Earth's crust where heat flow higher than in surrounding areas heats the water contained in permeable rocks (reservoirs) at depth. The resources with the highest energy potential are mainly concentrated on the boundaries between plates, where visible geothermal activity frequently exists. By geothermal activity we mean hot springs, fumaroles, steam vents, and geysers. Active volcanoes are also a kind of geothermal activity, on a particularly and more spectacular large scale.

Geothermal activity in an area is certainly the first significant indication that subsurface rocks in the area are warmer than the norm. The local heat source could be a magma body at 600–1000°C, intruded within a few kilometres of the surface. However, geothermal fields can also form in regions unaffected by recent (Quaternary) shallow magmatic intrusions. The anomalous higher heat flow may be due to particular tectonic situations, for example to thinning of the continental crust, which implies the upwelling of the crust-mantle boundary and consequently higher temperatures at shallower depths.

However, we need more than a thermal anomaly to have a productive geothermal resource. We also need a reservoir, which is a sufficiently large body of permeable rocks at a depth accessible by drilling. This body of rock must contain large amounts of fluids, water or steam, which carry the heat to the surface. The reservoir is bounded by cooler rocks hydraulically connected to the hot reservoir by fractures and fissures, which provide channels for rainwater to penetrate underground. These cooler rocks crop out at the surface where they represent the so-called *recharge areas* of the geothermal reservoir. Thermal waters or steam are, in fact, mainly rainwater that infiltrates into the recharge areas at the surface and proceeds to depth, increasing in temperature while penetrating the hot rocks of the reservoir (Fig. 1).

Water moves inside the reservoir by convection, due to density variations caused by temperature, transferring heat from the lowest parts of the reservoir to its upper parts. The result of the convection process is that temperature in the upper parts of the reservoir is not much lower that the temperature of its deeper parts, so that the lowest values of the geothermal gradient are actually found inside the reservoir. Convection, implying a real transfer of matter, is therefore a more efficient process of heat transfer than conduction, the other mechanism of heat transfer typical of less permeable rocks. Heat is transferred by conduction from the magma body towards the permeable reservoir rocks, the reservoir, filled with fluids.

Hot fluids often escape from the reservoir and reach the surface, producing the visible geothermal activity described above.

3.2. Hydrothermal systems

The heat source, the reservoir, the recharge area and the connecting paths through which cool superficial water penetrates the reservoir and, in most cases, escapes back to the surface, compose the *hydrothermal system*. The type of hydrothermal system that can support economic geothermal energy developments, particularly in electricity generation, is where magmatic intrusions are emplaced high enough in the crust that they induce the convective circulation of groundwater. They may or may not be related to eruptive volcanic activity. The heat output of hydrothermal systems varies with time. They generally occupy zones of structural weakness, where repeated magmatism is to be expected. The reservoir is the most important part of the system, from the point of view of energy utilisation, and in fact we define the reservoir "*as the hot part of the geothermal system that can be exploited either by extracting the fluid contained (water, steam, or various gases), or using anyhow its heat*" [6]. Existence of a hydrothermal system will not necessarily ensure production at industrial levels. Only a part of its rocks may be permeable, constituting a fluid reservoir, so that the system will be able to produce industrially from that part only. This part is called a *geothermal field*, and the geographic name of the locality usually gives its name to the field (for example, The Geysers geothermal field in California, Tiwi field in the Philippines, Wairakei field in New Zealand, Larderello field in Italy).

Four types of geothermal systems have been identified: *hydrothermal, hot dry rock*, *geopressured* and *magmatic*. The systems exploited at present are the hydro-

thermal systems. The other three may be exploited industrially in the future after more technological development.

Hydrothermal systems (or geothermal reservoirs, or fields) are traditionally classified as:

- water-dominated or
- vapour-dominated,

the latter having a higher energy content per unit fluid mass.

Water-dominated fields are further divided into hot water fields, producing hot water, and fields producing mixtures of water and steam, called wet steam fields.

3.2.1. Water-dominated fields

3.2.1.1. Hot water fields They are capable of producing hot water at the surface at temperatures up to 100°C. They are the geothermal fields with the lowest temperature, and the reservoir contains water in liquid phase. The reservoir may not have a cover of impermeable rock acting as a lid, however some of these thermal aquifers are overlain by confining layers that keep the hot water under pressure. Temperatures in the reservoir remain below the boiling point of water at any pressure because the heat source is not large enough. Surface temperature is not higher than boiling temperature of water at atmospheric pressure.

These fields may also occur in areas with normal heat flow. On the surface there are often thermal springs whose temperatures are, in some cases, near the boiling point of water. A hot water field is of economic interest if the reservoir is found at a depth of less than 2 km, if the salt content of the water is lower than 60 g/kg, and if the wells have high flow-rates (above 150 t/h). The best known examples of exploited hot water fields are those of the Pannonian basin (Hungary), the Paris basin (France), the Aquitanian basin (France), many Russian fields, the Po river valley (Italy), Klamath Falls (Oregon, USA), and Tianjin (China).

3.2.1.2. Wet steam fields They contain pressurised water at temperatures exceeding 100°C and small quantities of steam in the shallower, lower pressure parts of the reservoir. The dominant phase in the reservoir is the liquid one, and it is this phase that controls the pressure inside the reservoir. Steam is not uniformly present, occurring in the form of bubbles surrounded by liquid water, and does not noticeably affect fluid pressure.

An impermeable cap-rock generally exist to prevent the fluid from escaping to the surface, thus keeping it under pressure. This is common, but not absolutely necessary. In fact, at any depth below the water table, water bears its own hydrostatic pressure. When the fluid is brought to the surface and its pressure decreases, a fraction of fluid is flashed into steam, while the greater part remains as boiling water. Once a well penetrates a reservoir of this type, the pressurised water rises into the well because pressure is lower there. The consequence of the pressure drop is the vaporisation of part of the water, with the result that the well eventually produces hot water and steam, with water as the predominant phase. The water-steam ratio

varies from field to field, and even from one well to the next within the same field. As in many cases only steam is used to produce electrical energy, liquid water must be removed at the surface in special separators.

The surface manifestations of these fields include boiling springs and geysers. The heat source is large and generally of magmatic origin. The water produced often contains large quantities of chemicals (from 1 to over 100 g/kg of fluid, in some fields up to 350 g/kg). These chemicals may cause severe scaling problems to pipelines and plants. They are mainly chlorides, bicarbonates, sulfates, borates, fluorides and silica.

More than 90% of the hydrothermal reservoirs exploited on an industrial scale are of the wet steam type. Electricity generation is their optimal utilisation. One important economic aspect of wet steam fields is the large quantity of water extracted with the steam (for example 6600 t/h at Cerro Prieto, Mexico). Owing to its generally high chemical content this water has to be disposed of through reinjection wells drilled at the margins of the reservoir.

Examples of wet steam fields producing electricity, are: Cerro Prieto, Los Azufres and Los Humeros (Mexico), Momotombo (Nicaragua), Ahuachapán-Chipilapa (El Salvador), Miravalles (Costa Rica), Zunil (Guatemala), Wairakei, Ohaaki and Kawerau (New Zealand), Salton Sea, Coso and Casa Diablo (California), Puna (Hawaii), Soda Lake, Steamboat and Brady Hot Springs (Nevada), Cove Fort (Utah), Dieng and Salak (Indonesia), Mak-Ban, Tiwi, Tongonan, Palinpinon and Bac Man (Philippines), Pauzhetskaya and Mutnovsky (Russia), Fang (Thailand), Kakkonda, Hatchobaru and Mori (Japan), Olkaria (Kenya), Krafla (Iceland), Azores (Portugal), Kizildere (Turkey), Latera (Italy), Milos (Greece) (Fig. 3).

3.2.2. Vapour-dominated fields

Vapour-dominated reservoirs (fields) produce dry saturated, or slightly superheated steam at pressures above atmospheric. They are geologically similar to wet steam fields, but the heat transfer from depth is certainly much higher. Research suggests that their permeability is lower than in wet steam fields, and the presence of the caprock is of fundamental importance here. Water and steam co-exist, but steam is the continuous predominant phase, regulating the pressure in the reservoir: the pressure is practically constant throughout the reservoir. These fields are called dry or superheated fields. Produced steam is in fact generally superheated, with small quantities of other gases, mainly CO_2 and H_2S (Fig. 1).

The mechanism governing production in these fields is believed to be the following. When a well penetrates the reservoir and production begins, a depressurised zone forms at well-bottom. This pressure drop produces boiling and vaporisation of the liquid water in the surrounding rock mass. A dry area, i.e. without liquid water, forms near the well-bottom and steam flows through this zone. Steam crossing the dry area starts to expand and cool, but the addition of heat from the very hot surrounding rocks keeps steam temperature above the vaporisation value for the pressure existing at that point. As a result, the well produces superheated steam with a degree of superheating which may reach 100°C, for example with wellhead pressures of 5–10 bar (0.5–1 MPa) and a steam outlet temperature of more than 200°C.

Surface geothermal activity associated with vapour-dominated fields, whether dry

or superheated, is similar to the activity present in wet steam fields. About half of the geothermal electric energy generated in the world comes from six vapour-dominated fields: Larderello (Italy) (Fig. 5), Mt. Amiata, (Italy), The Geysers (California) (Fig. 6), Matsukawa (Japan) (Fig. 7), Kamojang and Darajat (Indonesia).

Of the approximately 100 hydrothermal systems that have been investigated, less than 10% are vapour-dominated, 60% are wet steam fields (water-dominated), and 30% produce hot water [7].

3.3. The chemical composition of steam

The average steam composition of some geothermal fields under exploitation is given in Table 1. Geothermal steam often contains gases such as CO_2, H_2S, HCl, HF, NH_3, CH_4, H_2, in a range that varies from field to field. In a particular field the content of these gases tend to decrease with time as a result of production.

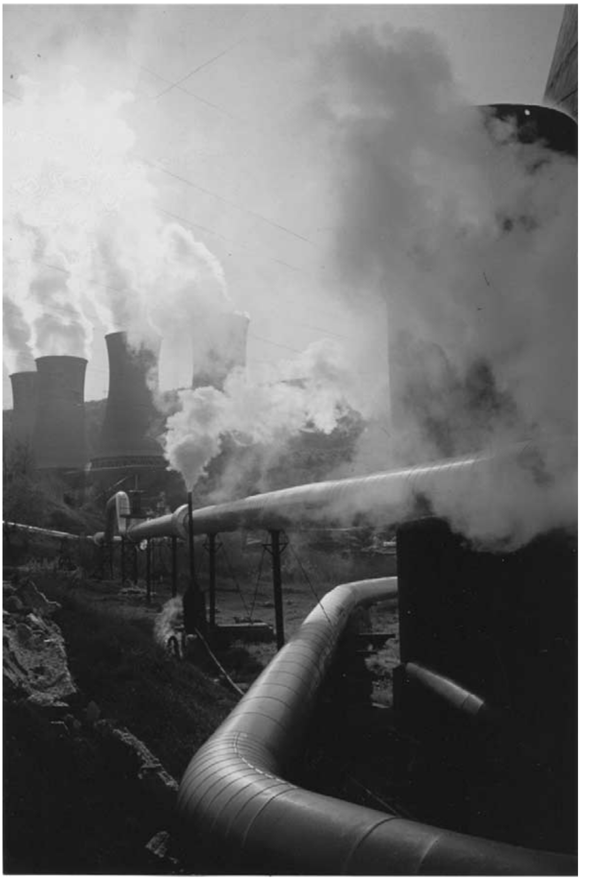


Fig. 5. Larderello geothermal steamfield, Tuscany, Italy. The installed geothermal electric capacity of the field was 547 MW_e in year 2000.



Fig. 6. A steamwell just drilled in the vapour-dominated field of The Geysers, California.

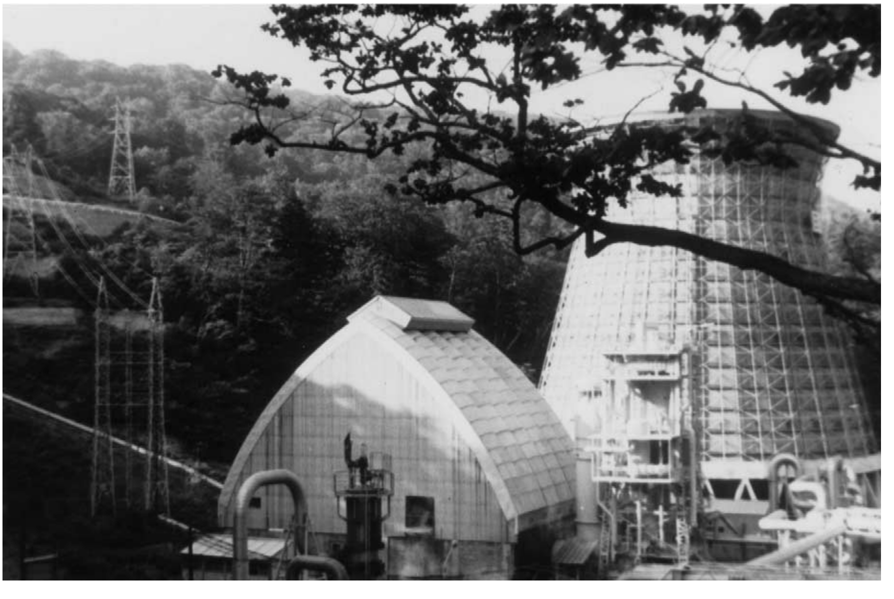


Fig. 7. Matsukawa geothermal power plant, the oldest plant in Japan, 23.5 MW_e.

Table 1
Composition of steam from some geothermal fields. Source [44]

Constituents g/kg	THE GEYSERS USA	LARDERELLO Italy	MATSUKAWA Japan	WAIRAKEI New Zealand	CERRO PRIETO Mexico
H_2O	995.9	953.2	986.3	997.5	984.3
CO_2	3.3	45.2	12.4	2.3	14.1
H_2S	0.2	0.8	1.2	0.1	1.5
NH_3	0.2	0.2			0.1
$CH_4 + H_2$	0.2	0.3			
Others	0.2	0.3	0.1	0.1	

3.4. Is geothermal a renewable source?

Shut-in pressures measured at the wellhead always decline with time as a consequence of fluid extraction and depletion of the reservoir. Geothermal energy has often been said to be a renewable energy resource. However, on the time scale normally used in human society, geothermal resources are not, strictly speaking, renewable. They are renewable only if the heat extraction rate does not exceed the reservoir replenishment rate. Exploitation through wells, sometimes using downhole pumps in the case of non-electrical uses, leads to the extraction of very large quantities of fluid, and consequently to a reduction or depletion of the geothermal resource in place.

Disposal of the spent cooled fluid after use, is also an important operation in each geothermal application. In electrical uses, steam condensates into a water that is often rich in salts, and this polluting waste must be disposed of accordingly. More than 95% of the fluid produced is often reinjected into the reservoir as water, contributing to limit pressure losses and to replace at least part of the fluid extracted. Models provide an invaluable help in the selection of reinjection areas, the depth of reinjection, and the optimal fluid reinjection rate.

The key to a successful geothermal project is to ensure, by careful reservoir evaluation and monitoring, that the geothermal reservoir will last for the lifetime of the geothermal installations. Experience has taught us that good reservoir management practices can assure an adequate steam supply for many decades.

3.5. The origin of steam

The first scientifically sound hypothesis on the origin of geothermal fields was advanced by the Italian geologist Bernardino Lotti at the beginning of 1900. At that time, Larderello geothermal field in Tuscany, Italy, was the only field to have been studied geologically, due to the industrial extraction of the boric acid from the thermal springs and natural steam issuing from shallow wells in the area. Lotti attempted to explain the origin of the vast quantities of boric acid in the hot fluids of this part of Tuscany. It was already known at that time that granite magma can contain water,

which is released during the cooling of the magma and its crystallisation process, both occurring at depth. Lotti concluded that the boron-rich steam and water at Larderello originated from a deep magmatic intrusion, and that steam reached the surface through faults and fissures connected with the magmatic body, thus acting as channels for the fluids to flow to the surface. Geothermal steam was, according to Lotti's hypothesis, of magmatic origin.

Lotti's hypothesis remained the only geological explanation for the origin of steam for more than half a century until the French geologist Jean Goguel, in a paper published in 1953 on the thermal regime of underground waters [8], presented his views on this issue, which overturned the previous concepts on a thermodynamic basis. Goguel showed analytically that a granite body undergoing cooling at depth can heat rainwater contained in overlying rock to boiling point, and that the main origin of steam is rainwater that percolates into the reservoir from the surface. A small percentage ($<10\%$) of the steam could however still be of magmatic origin.

Goguel's theory on the meteoric origin of steam and hot water was confirmed independently in 1956 and 1963 by the geochemists H. Craig, G. Boato and D.E. White [9], who studied the isotopic composition of the ratios hydrogen/deuterium and oxygen-16/oxygen-18 of the thermal waters and the rainwater of the same localities. The isotopic signature of the fluids showed that they had the same deuterium signature as that of local meteoric water and could not be magmatic. Solutes in geothermal fluids could on the contrary be derived from rock-water reactions, in fact Ellis and Mahon [10,11] and Mahon [12] demonstrated that all the solutes in geothermal fluids could be derived from reactions between the meteoric groundwater and the host lithologies. While there is no doubt that the geothermal fluids are of a predominantly meteoric origin, there is sufficient latitude in the isotope data to permit 5–10% of the fluid to be from an alternative source, possibly a magmatic brine. Mixing with even a small amount of magmatic brine would significantly affect the chemistry of the final geothermal fluid, and isotope determinations cannot discount a magmatic contribution subsequently diluted by meteoric waters. Furthermore, geochemical considerations indicate that unrealistically large volumes of rock would have to be leached over the lifetime of a geothermal system. A small, but significant magmatic contribution to the geothermal fluid is therefore thought to be likely [13].

A curiosity: the meteoric origin of the water of thermal springs and steam vents had already been clearly hypothesised more than three centuries ago, without of course any scientific proof. The Jesuit Father Athanasius Kircher, distinguished naturalist, in his book *Mundus Subterraneus* (The underground world) published in Amsterdam in 1678 and enriched with beautiful drawings, maintained that if the fire within the bowels of the Earth (i.e. the magma) passes near underground caverns filled with water, when this water is heated or vaporised and comes to the surface, it will emerge in the form of hot springs or fumaroles [14].

Linking the origin of geothermal steam to rainwater rather than to magma, was to have an important effect on the exploration and development of a geothermal field, by radically changing the exploration targets. The wells were no longer targeted at the steam conduits (faults and fractures) carrying the steam from magma to the shallower rocks, but were concentrated on areas that showed evidence of the exist-

ence of a deep geothermal reservoir with an adequate volume of permeable rock able to contain hot fluids, and of the presence of a heat source and a fluid recharge area at the surface, feeding the reservoir at depth. Another, no less significant consequence concerned the exploitation of a geothermal field. When steam was thought to be of magmatic origin, little thought was given to the hydrogeological conditions of the field, as the water contained in a granite magma was supposed to be able to sustain production for a long time. A meteoric origin, on the other hand, entails some considerations of the hydraulic and thermal balance of the field, as the hot water and steam produced by the wells must be replaced, at least partially, by rainwater. This water infiltrates to depths in areas that may be far from the field, and has to be heated by the hot rocks through which it moves. The consequence of this new understanding of the origin of steam is the currently accepted view that geothermal energy is not entirely a renewable energy source, as experience has shown that fluids are generally extracted at a faster rate than they are replaced in the reservoir.

3.6. The chemistry of geothermal fluids

3.6.1. Water chemistry

Mineral-fluid equilibria play a fundamental role in determining the chemistry of the discharge fluids. The reactions which take place are a function of the temperature, pressure, salinity and host rocks of the geothermal system. The product of mineral-fluid reactions is an assemblage of secondary alteration minerals.

In geothermal waters solute concentrations vary greatly and these differences are due to variations in temperature, gas content, heat source, rock type, permeability, age of the hydrothermal system and fluid source or mixing (for example with sea water). The following species are the most common:

- Anions (negative electrically-charged ions) Cl, HCO_3^- , SO_4^{2-}, F^-, Br^-, I^-
- Cations (positive ions) Na^+, K^+, Li^+, Ca^{2+}, Mg^{2+}, Rb^+, Cs^+, Mn^{2+}, Fe^{2+}
- Neutral: SiO_2, NH_3, As, B, noble gases.

In water-dominated geothermal systems the most common type of fluid found at depth, the primary water type, is of near-neutral pH, a sodium-chloride brine (with 1000–10,000 mg/kg of Cl) containing gas, mainly CO_2. It is generally agreed that these waters are formed, at some greater depth, from the absorption of magmatic volatiles (HCl, CO_2, SO_2, H_2S) into deeply circulating meteoric water. The proportion of magmatic volatiles ultimately determines the salinity of the reservoir waters (except where seawater is the primary source of chloride and Cl levels can exceed 100,000 mg/kg). Juvenile acid magmatic vapours and HCl-rich steam condensates are common at the surface of active volcanoes and occasionally are found in localised parts of younger or rejuvenated hydrothermal systems [15].

Chloride waters, also termed ‘alkali-chloride’ waters, are typical of deep geothermal fluids found in most high-temperature systems. Chloride fluid is commonly discharged from hot springs and from most geysers. Hot, chloride springs of good flow usually indicate a highly permeable feed zone [13].

Sulfate waters. They are also known as 'acid-sulfate waters' and are invariably superficial waters formed by the condensation of geothermal gases into near-surface, oxygenated groundwater. Such fluids are highly corrosive to well casing and surface pipelines.

Bicarbonate waters. These waters, which include those termed CO_2-rich fluids and neutral bicarbonate-sulfate waters, are the product of steam and gas condensation into poorly-oxygenated sub-surface groundwaters. They are highly corrosive on well casings.

Sulfate-chloride waters. These waters can form by several processes, of which the most common is the mixing of chloride and sulfate waters at variable depths.

3.6.2. Gas chemistry

Gases such as CO_2, H_2S, NH_3, N_2, H_2, and CH_4 are generally found in steam and are invariably present in geothermal discharges from both natural features and wells. These gases are often collectively referred to as the 'non-condensible gases' because they do not condense (become liquid) at the pressure of the electricity generating cycles, and therefore must be extracted from the condenser, and are usually exhausted to the atmosphere if H_2S levels do not exceed environmental standards. The terms 'steam', 'gas' and 'vapour' are all used in the geothermal literature. It is usual for the vapour phase to be called the steam phase, and this is not strictly correct because the vapour phase is composed predominantly of steam (water vapour) with a small proportion of gas (a few percent of the total). Steam from major geothermal fields has a content of non-condensible gases that ranges from 2.5 to 47 g/kg of steam (Table 1). However, although the proportion of gas within the steam discharge is small, the concentration of the gases together with the gas/steam and steam/water ratios can yield important information on the subsurface conditions and on the behaviour of a field during exploitation.

As with the water-soluble constituents, geothermal gases can be conveniently divided into two groups [13]:

- reactive gases (H_2O, CO_2, H_2S, NH_3, N_2, H_2, and CH_4) which take part in the chemical equilibria and provide information on the sub-surface conditions such as temperature;
- inert gases (noble gases, hydrocarbons other than methane) which act in an analogous manner to chloride in that they do not take part in chemical reactions. They can be used to provide information on the source of the gases.

Carbon dioxide (CO_2). This is the most abundant gas in geothermal systems, often representing over 85% by both volume and weight of the total gas content of a discharge. It ranges between 2.3–45.2 g/kg of fluid from major geothermal fields (Table 1).

Hydrogen sulfide (H_2S). This gas is very common in geothermal fluids and may be produced by alteration of the reservoir rocks or from a magmatic source. It ranges between 0.1–1.5 g/kg of fluid from major geothermal fields (Table 1).

Ammonia (NH_3). This is the most soluble of the geothermal gases. High concen-

trations of ammonia can result from the alteration of organic matter in sedimentary rocks at depth or in near-surface environment. NH_3 is carried in steam as a gas, but is highly soluble in water at lower temperature.

Hydrogen (H). A highly reactive gas, hydrogen is readily removed on reaction with wall rocks.

Methane (CH_4). Of all the hydrocarbon gases, methane is the most commonly encountered. High concentrations of methane can be produced by the alteration of sedimentary rocks at depth, particularly if organic-rich. The reaction of carbon dioxide and hydrogen, producing methane and water is commonly considered the most likely, but reactions between hydrogen and carbonaceous material have also been suggested. Concentrations of CH_4+H_2 in steam from The Geysers (California) and Larderello (Tuscany) ranges between 0.2–0.3 g/kg of fluid.

Nitrogen (N_2). As the principal atmospheric gas, most nitrogen in geothermal fluids is derived from that dissolved in the meteoric recharge waters, although it can also be of magmatic origin. Nitrogen tends to assume greater proportions in low-temperature systems where it can be the major gaseous component.

Noble gases. The atmospheric noble gases, helium, neon, argon, krypton and xenon are contributed to the geothermal fluid by the meteoric recharge waters and additionally for He and Ar by rock leaching reactions. Radiogenic He can make a significant contribution to the overall concentration of the gas, and in fact be the main source. Radiogenic Ar, on the contrary, has little impact on the total Ar content of the gas discharge. Helium in these fluids is largely of mantle origin. Helium formed by the radioactive decay of elements in the uranium-thorium series (entirely ^{4}He) can be introduced by fluids of deep crustal origin. In general, He and N_2 can be considered of deep source while argon reflects dilution by meteoric waters [15]. Radon (^{222}Rn), a gaseous radioactive isotope naturally present in the Earth's crust, is contained in the steam and discharged into the atmosphere.

Oxygen (O_2). The presence of oxygen in a gas sample often indicates contamination either by soil air or during the sample procedure, in fact oxygen contamination in uncontaminated samples is near or below the detection limit.

Hydrogen halides (HF, HCl). In water-dominated systems with chloride waters at depth, virtually no hydrogen halides will be found in the vapour phase. However, steam produced by boiling of acidic geothermal waters or derived from magmatic sources can contain significant concentrations of free HF and HCl.

Arsenic. It can enter the vapour phase as arsenous acid H_3AsO_3, but only in very high-temperature systems is arsenic likely to be more than a trace constituent.

Boron. The volatility of boron increases with increasing temperature, and although originally derived by rock leaching and concentrated in the liquid phase, significant quantities of boron can be transported as a vapour. The principal volatile boron species is boric acid (H_3BO_3). Boron is readily dissolved by steam condensate or near-surface steam-heated waters in which it attains elevated concentrations, it shows highest concentration in upflow zones (up to 484 mg/kg of fluid in Larderello geothermal field [16].

Mercury. Mercury vapour and gaseous HgS can both contribute to the mercury content of the steam discharge. Hydrogen sulfide concentration of the deep fluid play

an important role in controlling mercury emissions, with less mercury vapour being produced with increasing H_2S concentrations.

Tritium. (^3H). Tritium is the radioactive isotope of hydrogen, and deep geothermal fluids with long residence times commonly contain little tritium compared with modern surface waters. The tritium content of steam can therefore be used to differentiate between deep and shallow sources of the steam, to recognise mixing between steam from both deep and shallow sources, and to estimate the residence time of water or steam underground. Tritium is created in the atmosphere by the interaction of nitrogen with neutrons produced by cosmic radiation, and is transported into groundwaters by meteoric water. The tritium concentration levels in rains rose after a series of thermonuclear detonation tests in the 1950s and reached the peak concentrations two orders of magnitude above the natural level (for example in 1976–1980, there were still 50 T.U. (tritium units) in shallow waters in the geothermal field of Beppu, Japan [17]). The relatively short half life (12.43 yr) makes this isotope a valuable tracer of water movements happening over time spans of a century or less. The tritium concentration in natural waters, or in the steam condensate, is expressed by T.U. (tritium units), 1 T.U. corresponds to a concentration of 1 tritium atom per 10^{18} hydrogen atoms. Analysing the tritium content in a groundwater the following cases can occur:

- the water is tritium-free. This means that in the aquifer more than 40 years are required for the water to reach the sampling point from the recharge area;
- the tritium content is appreciable and variable with time. This means that an appreciable amount of water younger than 40 years is present and the variations imply a short circulation time of the order of a few years. Another possibility is that water from two different sources is present: a mixing of an old tritium-free water and a young water containing tritium;
- the tritium content is appreciable and constant in time. This means that the young water is well mixed in the aquifer with old water and the size of the reservoir masks any fluctuations in recharge [18].

4. The geologic environment of geothermal resources

It is widely accepted that most geothermal fields are localised in areas of young tectonism and volcanism (younger than Cenozoic, 65 million years before present), and primarily along active plate boundaries (Fig. 3). In fact, large volcanic-related hydrothermal systems only occur in areas where magma comes close to the surface, and this occurs at tectonic plate boundaries, and over mantle hot spots.

Diverging boundaries between plates are zones in which new crust is created by extensive igneous intrusion and extrusion and, accordingly, they are favourable sites for the presence of geothermal fields. Examples of mid-oceanic spreading ridges above sea level, and associated geothermal fields, are Iceland, the Azores islands, and the Afar depression in Ethiopia. There are also spreading ridges on continents: the East Pacific Rise, with the geothermal fields of Cerro Prieto (Mexico) and

Imperial Valley (USA), and the East African Rift, with the fields of Langano (Ethiopia) and Olkaria (Kenya).

Converging plate boundaries are those belts along which two plates move towards each other, resulting in the consumption of lithosphere by the thrusting of one plate beneath the other (the process called *subduction*). Melting of downthrust crust produces pods of magma that rise into the upper plate and act as heat sources for overlying geothermal reservoirs. Geothermal fields clearly related to subduction zones where oceanic plates bend downwards beneath a continental plate are those of Japan (near the contact between the Pacific plate and the Eurasian plate), Indonesia (Indian-Australian and Eurasian plates), New Zealand (Pacific and Indian-Australian plates), Chile and Central America (Nazca and South American plates) and, if their existence is proven, the fields in the Cascade Mountains in the western United States and on the island arcs of the Aleutian islands of Alaska.

Converging continental plates, where a collision takes place between continents, as in the case of the northwest part of the Indian-Australian and the Eurasian plates, produce conditions that are also favourable for the formation of geothermal fields. Examples are the Indian and Chinese Himalayan geothermal fields.

In the Mediterranean area, where the Eurasian and African continental plates collide, the crust is young and also shows the effects of the subduction of the African beneath the Eurasian plate. This is, in fact, the area of the Eolian and Hellenic trenches, the Tyrrhenian, Algerian-Provençal and Aegean marginal basins, and a system of tensional horsts and grabens (Tuscany, Latium and Campania, Italy) with associated active and recent volcanism. One important result of the rather irregular distribution of these geothermal areas is that the majority of Mediterranean countries are restricted to low temperature ($<100°C$) geothermal fields, and thus to non-electrical uses of heat, whereas the high temperature sources eligible for electricity generation are confined to central and southwest Italy, eastern Greece and west Turkey.

Intraplate melting anomalies are responsible for Quaternary volcanism (less than 2 million years old) and associated geothermal fields where mantle plumes rise beneath a continent (Yellowstone in the continental USA) or an oceanic plate (Hawaii). Rather than breaking up the plate, the plume acts as a heat source (or hot spot) beneath the moving plate. As the plate moves over the plume, a line of volcanoes forms. The volcanoes are gradually carried away from the eruptive centre, sinking as they go because of cooling.

5. Exploration for geothermal resources

Present technology and economic factors restrict extraction of geothermal energy to the upper few kilometres of the Earth's crust. Geothermal wells, to date, are drilled to less than 5 km depth.

As in the search for any natural resource, a strategy for geothermal energy exploration must be defined and followed. Once a geothermal region has been identified, the next step is to use various exploration techniques to locate the most interesting geothermal areas and identify suitable targets for fluid production.

It is necessary to estimate temperature, reservoir volume and permeability at depth, as well as to predict whether wells will produce steam or just hot water. Ideally we should also estimate the chemical composition of the fluid to be produced. To obtain this varied information, there are a number of exploration techniques available:

- inventory and survey of surface manifestations,
- geological and hydrogeological surveys,
- geochemical surveys,
- geophysical surveys, and finally
- exploratory wells.

To reduce the cost of exploration, it is normally approached in a prescribed sequence of steps, altering the order from time to time depending on our prior knowledge of the area in question. In some cases, high costs will lead to the elimination of some steps in the sequence.

5.1. Inventory and survey of surface manifestations

The knowledge of surface thermal manifestations (hot springs, steam vents, fumaroles, etc.) and their physical and chemical characteristics is of fundamental importance. This information, which can usually be obtained simply and at relatively low cost, is extremely useful for subsequent planning of exploration.

The surface survey is conducted in two consecutive phases: 1) the collation, processing and standardisation of published and recorded data relative to local manifestations (chemistry, temperature, flow-rates, etc.), and 2) the collection of new data, water samples, gas samples, temperature measurements, etc.

5.2. Geological and hydrogeological surveys

These are not limited to studies of groundwaters, but also include geological surveys that provide information on the stratigraphic and structural framework of the area. Geothermal reservoirs are often associated with volcanoes and volcanic regions and therefore volcanology also offers many examples of how geological field data give evidence of the location, nature and size of a geothermal resource [52].

Hydrogeological surveys permit us to correlate the hydrothermal manifestations with faults, fractures and other tectonic features. These surveys are aimed at identifying the distribution of confined and unconfined aquifers that will permit us to reconstruct the underground pattern of water circulation. Mathematical models have proved to be of great help in hydrogeological surveys.

5.2.1. Fluid inclusions

Fluid inclusions may give information on the temperature of deposition of inclusions and therefore determine the temperature and salinity of geothermal fluids. Fluid inclusions are defects in crystals, formed during or after deposition. All crystals

have inclusions. Some inclusions are solid, others empty, a few contain fluids. Inclusions need to be multi-phase (liquid and vapour) to be most useful.

5.3. Geochemical surveys

Geochemical exploration can start simultaneously with geologic and hydrogeologic reconnaissance, provided that springs and other geothermal manifestations are available for fluid sampling. Geochemical studies of geothermal fluids involve three main steps: 1) sample collection, 2) chemical analysis and 3) data interpretation. The types of samples collected are water samples from hot springs, steam samples from fumaroles, gas samples from hot pools [55].

Geothermometers enable to estimate the temperature of deep reservoirs by analysing hot fluids samples and calculating the ratios of certain chemical elements.

The content of tritium and ^{14}C radioisotopes permit us to evaluate the age of the geothermal fluids, that is, the time lapsed since their infiltration into the ground. Geochemical surveys with the use of tracers [50] can also offer information on the direction of movement of subsurface groundwaters and of rejniected fluids, and also the type of corrosion and scaling problems that could be encountered during the operation of wells and a plant.

Hydrogen and oxygen isotopes can be used to identify the recharge areas of the geothermal reservoirs, in fact the isotopic composition of a rain precipitation is dependent on its formation temperature [51].

5.3.1. Geothermometers

Geothermometers enable to estimate the temperature of deep reservoirs by analysing hot fluids samples and calculating the ratios of certain chemical elements (i.e., Na, K, Mg, Ca, etc.), and making some adjustment for the degree of mixing of the hot geothermal reservoir water with cooler groundwater in the shallow part of the hydrothermal system.

They are therefore valuable tools in the evaluation of new fields, and in monitoring the hydrology of systems on production. In fact, at particular temperatures, common assemblages of minerals will tend towards equilibrium with a given water chemistry. It has been noted that for certain parameters or ratios of parameters, the relationship between temperature and chemical composition will be stable and predictable. These parameters or ratios of parameters are known as *geothermometers*. In order for these to work, one has to assume that effects of dilution are insignificant and that thermodynamic equilibrium has been attained. In general geothermometers based on ratios will be more resistant to dilution effects than those based on absolute concentrations. In addition, it should be realised that the temperature indicated by the geothermometer is not necessarily the maximum temperature of the water, but the temperature at which mineral and water phases were last in equilibrium with respect to the phases in question [13].

The three principal indicators of deep reservoir temperatures, to be sought in hot spring chemistry, are *silica*, *magnesium* and *sodium/potassium* ratios. Silica concentrations are more reliable for hot springs of high discharge than those of low dis-

charge. Magnesium is of limited value as a temperature indicator, but its total absence could be suggestive of economically useful temperatures (at least 200°C), as magnesium is retained in clay rocks which are stable at high temperatures.

In vapour-dominated fields where the discharged fluid consists of almost pure steam with a limited number of volatile chemical species, *gas geothermometers* are of particular interest as nothing is known of the composition of the liquid phase from which the produced fluid originates. The concentrations and relative proportions of gases in geothermal steam are controlled by temperature-dependent fluid-mineral and gas-gas equilibria which have been used as the basis of gas geothermometers. However, the control these equilibria have over gas chemistry are not as well understood as the controls over water chemistry and there are some tenuous assumptions inherent in the development of the geothermometers. The majority of gas geothermometers require that the gas/steam and, for a hot water reservoir, the steam/water ratios are known. Since steam and the corresponding water phase rarely discharge at the surface together, these ratios cannot be determined for hot springs or fumaroles. This has therefore limited the application of most gas geothermometers to well discharges. The exception to this are the empirical geothermometer of D'Amore and Panichi based on the CO_2-H_2S-H_2-CH_4 system, and the CO (D'Amore), CO_2 (Arnorsson) and H-Ar (Arnorsson and Gunlaugsson) geothermometers. These can be applied to both natural and well steam discharges.

5.4. Geophysical surveys

Classical geophysical techniques, namely, seismic, gravity and magnetic surveys as applied to geothermal research, can be defined as *indirect* methods. These methods, in fact, are not directly associated with the properties of the hot fluids that are being sought. Rather, they yield information about the attitude and nature of the host rocks. However, there are other geophysical methods that may *directly* reveal variations in the physical properties of the rocks caused by the presence of hot and saline fluids. These techniques include electrical-resistivity, electromagnetic and thermal-measurement methods.

5.4.1. Seismic surveys

Elastic waves are transmitted through rocks, and their velocities can be used to help determine the structure and properties of rock bodies. Seismic waves are introduced into the Earth by detonating an explosive charge in a shallow borehole or by using a large mass to thump the surface. Returns of seismic waves are measured at the surface. Seismic waves also originate naturally from earthquakes and microearthquakes, and these waves can also be detected at the surface. Interpretation of the seismic information can provide data on the location of active faults that can channel hot fluids towards the surface.

5.4.2. Gravity surveys

Variations in the Earth's gravity field are caused by changes in the density of subsurface rocks. Gravity surveys are rather simple and inexpensive. Gravity anomal-

ies alone are not necessarily indicative of a geothermal region, but they do give valuable information on the type of rocks at depth and their distribution and geometric characteristics.

5.4.3. Magnetic surveys

The Earth has a primary magnetic field which induces a magnetic response in certain minerals at and near the Earth's surface. By detecting spatial changes of the magnetic field, the variations in distribution of magnetic minerals may be deduced and related to geologic structure. However, each magnetic mineral has a Curie temperature, above which it loses its magnetic properties. For iron, the Curie temperature is 760°C. Aeromagnetic surveys are much more commonly used in geothermal exploration than ground based surveys. The basic principle is to detect zones which are magnetically featureless, due to destruction of magnetite in near-surface rocks by hydrothermal alteration. The usefulness of magnetic surveys in geothermal exploration is controversial.

5.4.4. Electrical-resistivity surveys

Most electrical methods are based on measurement of the electrical resistivity of the subsurface. Resistivity in the Earth is often largely affected by electrical conduction within waters occupying the pore spaces in the rock. Consequently, resistivity varies considerably with porosity. Temperature and salinity of interstitial fluids tend to be higher in geothermal reservoirs than in the surrounding rocks. Consequently, the resistivity of geothermal reservoirs is generally relatively low. It is this contrast in resistivity between hot water-saturated rocks and the surrounding colder rocks that is used in resistivity surveys. These techniques are based on injection of current into the ground and measurement of voltage differences produced as a consequence at the ground surface.

One of the major drawbacks with electrical methods is the shallow depth of penetration.

5.4.5. Electromagnetic surveys

Induction or electromagnetic methods are a tool for determining the electrical resistivity distribution in the Earth by means of surface measurements of transient electric and magnetic fields. These fields can be naturally or artificially generated. These methods are more suitable for measuring the low resistivities of geothermal reservoirs than the above-mentioned electrical-resistivity methods. Furthermore, in geothermal areas the surface resistivity is sometimes so high as to prevent current from entering the ground, and the electromagnetic methods, with a much deeper penetration, help eliminate the screening effect of very resistive surface rocks. Currents of varying frequency (generally from a few to several tens of thousands of Hz) are transmitted into the ground, either via the electrodes as in the electrical methods, or by induction loops. Mobile stations measure, at several points, the electrical and magnetic fields created by this transmission. Comparison between these fields enable the resistivities of the underlying formations to be obtained, as a function of the frequency used, that is as a function of the depth, as in the magnetotelluric soundings (MT).

Magnetotelluric soundings use natural oscillations of the Earth's electromagnetic field to determine the resistivity structure of the sub-surface. The electromagnetic waves are assumed to be planar and nearly vertically incident on the surface of the Earth where they are detected. The lower the frequency, the deeper the penetration is taken to be, but the longer it takes to collect a signal with a satisfactory signal to noise ratio. The depth of penetration of MT surveys is also much greater than of during current (DC) resistivity measurements, and it is often possible to achieve a penetration as great as 3–5 km with a reasonable degree of precision and in a reasonable period of time, this can be compared to a maximum depth of penetration from most DC methods of less than 2 km. MT does not require a current source.

5.4.6. Thermal-measurement surveys

In geothermal research the traditional geophysical methods mentioned above, which originally had been developed for the oil industry, are used side-by-side with more specific techniques. Geothermal prospecting provides information on the thermal conditions of the subsurface, the areal distribution of the Earth's heat flow, and the location and intensity of thermal anomalies. To be more specific, geothermal prospecting allows us:

- to verify the existence of high-temperature fluids in areas without surface manifestations, but in which the geostructural and hydrogeological situation is favourable to hydrothermal circulation;
- to more precisely site deep drilling in areas that are considered potentially productive;
- to delineate the boundaries of geothermal fields that have been identified, so as to avoid drilling of dry holes in non-productive marginal areas;
- to acquire data for evaluation of the geothermal potential of the field.

Heat flow measurements are made by drilling small diameter (4 inches, 10 cm), shallow wells (generally <300 m), the number of which depends on local conditions and on the results one wants to achieve. Generally, heat flow is measured every 10–25 km^2. The depth of the wells must be such as to avoid the effects of propagation of the annual surface thermal variations, which are negligible beyond 20 meters, and the thermal disturbances caused by the circulation of shallow ground waters.

The geothermal gradient is obtained from temperatures measured with electric thermometers at various depths along a well. Temperature logging is quick and relatively inexpensive. The thermal conductivity of the rocks in the interval in which the gradient has been measured is usually determined by laboratory measurements on core samples. The product of the gradient and conductivity gives the *heat flow*.

Sometimes gradient values alone are sufficient to give the information required. However, this is possible only if the survey is carried out in areas that are lithologically homogeneous at depth, in which the thermal conductivity can be considered constant.

In geothermal areas the heat flow is higher than the general background level, so that high heat flow values are a good indicator of underlying geothermal resources [49].

5.5. Exploratory wells

The final stage of an exploration survey is exploratory well drilling. Usually the final diameters of these wells are on the order of 8 inches (20 cm) or less, allowing the insertion of special logging tools to measure various parameters from the surface to total depth, and sometimes to carry out fluid production tests. A pump may be lowered into a shallow hot water well some hundreds of meters deep, and compressed air (gas lift) may be injected in deeper hot water wells.

Since most geothermal reservoirs are made up of fluid-filled fractures, it is essential that an exploratory well intersects as many fractures as possible. In some cases it may be necessary to redrill the well at an angle in order to intersect the natural fracture pattern. Since natural fractures are related to tectonic activity (folding and faulting), the siting of exploratory wells is greatly dependent on our geologic interpretation of the local structural conditions.

6. Drilling, extraction and distribution of fluids

6.1. High-temperature wells (>150°C)

Drilling and completion of wells are the most critical operations in the development of a geothermal project. Drilling for geothermal fluids is similar to rotary drilling for oil and gas (Fig. 8). However, geothermal drilling is generally more difficult than in oil and gas operations due to the nature of the rock being penetrated and the higher temperatures and corrosive nature of the fluids. The rock is usually harder, metamorphic or igneous rather than sedimentary, and the high temperatures associated with geothermal wells affect the circulation system and the cementing procedures as well as the design of the drill string and casing. To prevent blow-outs of high-temperature wells during drilling, safety devices called blow-out preventers are used.

Mud is generally used as the drilling fluid, but the use of air instead of mud makes drilling much faster and cheaper and has been adopted frequently in recent years. One major obstacle in air drilling in geothermal areas is its unsuitability in formations carrying excessive water or in formations that tend to collapse.

Directional drilling techniques are used in areas where the surface directly above a drilling target is unavailable, when a well pad cannot be constructed for economic or environmental reasons, or when a single pad is to be used for several wells (Fig. 9). The angle is established and maintained by utilising a downhole turbine drill. Directionally drilled wells cost about 25% more than vertically drilled wells, in part because of slower penetration rates.

The hottest geothermal well drilled so far is located in the Kakkonda field, Japan, where 500°C have been measured by temperature indication materials (melting point of tellurium and other substances) at the depth of 3729 m in Quaternary granite [19].

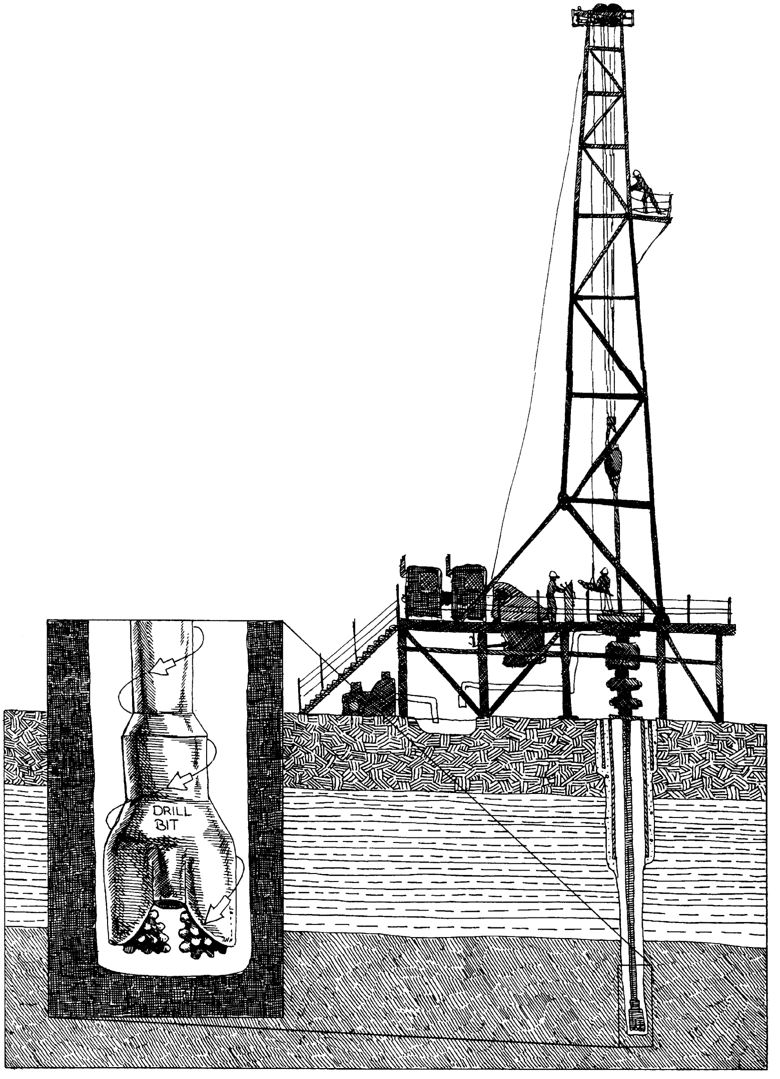


Fig. 8. A drilling rig and the drilling bit. The bit is lowered to the ground and turned. As it turns, rock is chipped away. Source [45].

6.2. Cost of drilling

Due to the hardness of the rock, and the high probability of encountering lost-circulation zones where drilling fluids can disappear into the rock fractures, the cost of drilling can run as high as 50% of the total cost of a project. Rig rental rates run at US$10,000/day or more, which together with the cost of the casings, drilling fluids, drill bits, other consumable items and third party services for cementing, directional

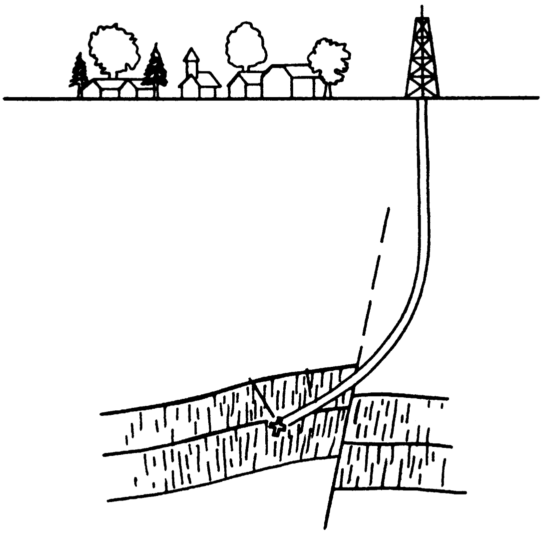


Fig. 9. Scheme of a directionally drilled well. This technique is used when the area directly above the drilling target is unavailable. Source [21].

drilling, etc. lead to finished well costs in the range of US$1.5–3 million, with a cost per drilled meter of US$800–1200/m (1998), and commercial well depth is generally set at a maximum of 3 km [15].

Drilling success is, on average, 50% in developed geothermal fields (Fig. 10). The



Fig. 10. A steamwell feeding a power plant in the Larderello area, Tuscany.

world figures for power from 29 producing fields and 2230 wells are 0.3–4.8 MW_e/well, and the weighted average 1.9 MW_e/well [20].

6.3. Low-temperature wells (<150°C)

Drilling and casing of a low-temperature well is probably the most expensive activity in geothermal projects for non-electrical uses. Present drilling technology is expensive, and the costs are rising rapidly. Costs of all wells increase exponentially with depth. The cost of drilling into many low-temperature geothermal reservoirs will make them uneconomic for production. Also, added to the actual cost of drilling are the costs for land acquisition and geological surveys.

The technology required for drilling into low-temperature geothermal reservoirs is similar to that used for ground water wells. The primary aspect when drilling into these reservoirs is cost, and low-temperature wells deeper than 2 km are generally not considered economic.

6.4. Extraction of fluids

The flowrate from, and the performance of a geothermal reservoir are functions of many parameters. Among these are the volume and type of the fluid in the aquifer, the rate of recharge (if any), the permeability of the rocks, the design of the drilled well and piping, and the type of completion equipment utilised (e.g., pumps in low-temperature wells).

Depending on the characteristics of the particular reservoir, the fluid may exist at the surface as a liquid, a vapour, or a mixture of the two, and may also include various dissolved gases and solid material. Thus, the type of equipment necessary to extract the fluid from the reservoir will depend on the enthalpy-pressure characteristics of the fluid and its salt content. For low-temperature fluids, of interest in non-electrical applications, we will generally be looking for fluid in the liquid phase.

6.5. Well-testing

Well testing is a critical phase in the development of a geothermal resource, particularly at the exploration stage. For the first time the nature of the deep geothermal reservoir is revealed and direct information on the chemistry of the deep fluids is obtained. Well testing commences immediately upon completion of a well, may continue for several months, and provides information on the suitability of the well and the reservoir for power generation or other uses. Well testing includes physical well measurements conducted by reservoir engineering personnel under both shut-in and flowing conditions and chemical analysis of discharge and downhole fluids.

Depending on the well conditions, logging can provide information on temperature, depth, pressures at various points, types of rock and their permeability, porosity, and fluid content. Fractures met by the well at depth can be located, and fluid production zones can be identified [21]. This information is of primary importance to reservoir engineers and to geologists, geophysicists and geochemists, who use it to

confirm and refine their interpretation of the deep geological structures and of the thermal and hydrogeological conditions in the subsurface, hypothesised beforehand by means of geological, geophysical and geochemical surveys carried out at the surface.

The most difficult but fundamental parameters to be determined are the size of the reservoir and its energy potential. It is therefore evident that long production tests must be carried out correctly as they are the key to decide whether further investments are advisable in the field, and the best economic use of the resource. To recover exploration and development costs, a geothermal field must keep the fluid extraction rate reasonably constant over many years, at least several decades. Geothermal reservoir models are of great help in providing this information.

6.6. Reservoir modelling

Geothermal reservoir modelling provides quantitative estimates of future fluid flow from wells exploiting the reservoir. The predicted well performance is determined by the future fluid state (pressure, temperature, enthalpy, etc.) in the reservoir, and results are usually presented in the form of changes in the reservoir [22,23]. A quantitative model must be validated against field data. The distinctive test of a model is its ability to reproduce known behaviour. Mathematical models are implemented with the help of computers. With a good model the optimum fluid production and the subsequent reinjection rate of the waste back into the peripheral parts of the reservoir can be quantified and projected over several years.

6.7. Distribution of fluids

Production-gathering systems transport the produced fluids, steam or water, from the wells to the power plants or other utilisation facilities, such as buildings or greenhouses. Vapour-dominated reservoirs produce dry steam, which goes directly from the wells to the power plants. In water-dominated reservoirs which produce water and steam (and not hot water only), the fluid from the wells is sent into separators, located on the well pads. The separator allows a portion of the fluid (15–20%) to flash into steam, which is then directed through pipelines to the power plant. The condensed steam and the remaining waste water are then generally discharged back into reinjection wells.

In the non-electrical uses (direct uses) of geothermal energy, a hot water distribution network is required. Its cost may represent a major part of the total system cost. The network is an assembly of piping that varies in size throughout the system depending on the flowrates through the various branches (Fig. 11). These systems also require pumps, valves, meters, expansion joints, and the controls necessary for reliable operation of the network. The system is generally thermally insulated to prevent excessive heat loss and temperature drop in the fluid.

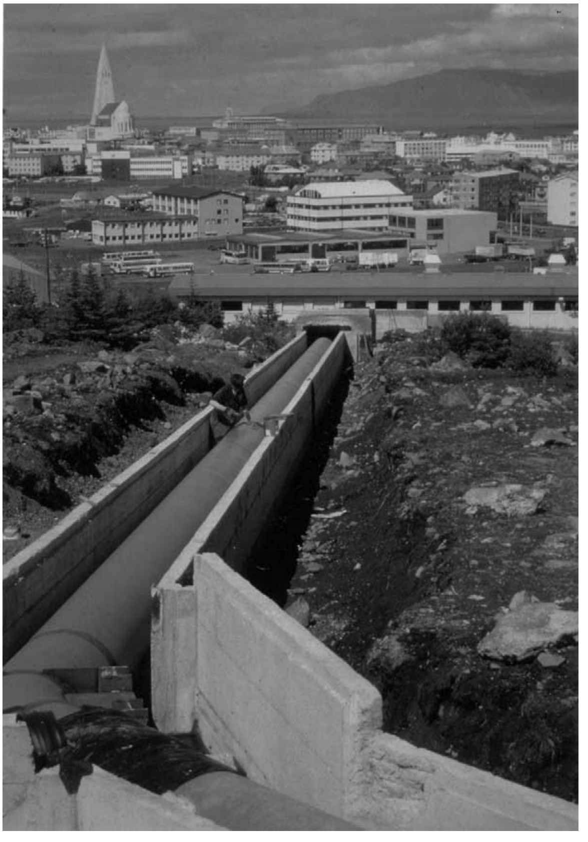


Fig. 11. Insulated pipes of the geothermal water distribution network for district heating, Reykjavik, Iceland. (Courtesy of G. Palmason, Iceland).

7. Resource assessment

For any geothermal field a series of resource assessments will be made during the exploration and development process. As more data become available the resource assessment will become more certain. It is important that at each stage the uncertainties are fully appreciated and the level of detail is appropriate without giving a false impression of precision. The main requirements for a good resource can be summarised as follows [15]:

- a high temperature for good power plant efficiency;
- a large quantity of stored heat for resource longevity;
- a low rate of liquid production per unit of energy (in case of electricity generation);
- rejniection well sites available at a lower elevation than production for disposal under gravity;

- produced fluids with a near-neutral pH for low corrosion rates in wells and plants;
- adequate permeability to ensure adequate outputs from individual wells;
- a low tendency for scaling in pipelines and wells;
- low elevation and easy terrain for access roads;
- a low risk of vulcanicity and hydrothermal eruptions;
- proximity to electrical load or transmission lines.

At an early stage in exploration, prior to drilling, resource assessment is largely qualitative.

Once a few wells have been drilled, it will be possible to undertake a more accurate resource assessment.

Resource assessment during production is more in the realm of reservoir engineering. Once production data are available it may be apparent that the resource is capable of sustaining more production than the first stage plant can handle, or viceversa that the power plant has been over-sized for the resource and that additional resources will have to be found or the plant be decommissioned. There will need to be a continuing scientific input to assess resource capacity.

8. Resource sustainability

The term '*sustainable development*' is used to mean development that meets the needs of the present generation without compromising the needs of future generations. In the strictest sense, the sustainability of a resource is dependent on its initial quantity, its rate of generation and its rate of consumption [24]. Consumption can obviously be sustained over any time period in which a resource is being created faster than it is being depleted. If the rate of consumption exceeds the rate of generation, consumption can nevertheless be sustained over some time period dependent upon the initial amount of the resource available when consumption begins.

The sustainability of production from geothermal resources is a topic that has received almost no study, leaving the question open to conjecture. As geologic phenomena, hydrothermal systems in the continental crust can be shown to persist for tens of thousands of years. However systems lifetimes can be foreshortened by artificial production at the surface during geothermal energy extraction. Geothermal project feasibility studies typically deal only with developing a certain sized power plant to be run for an arbitrary period, usually 30 years. Such limited studies fail to capture a true measure of the useful energy that can be produced from a geothermal resource. New studies will hopefully provide estimates of the sustainability of production from geothermal resources.

9. Utilisation of geothermal resources

9.1. Historical outline

Practical uses of geothermal energy, for bathing, washing and cooking, date back to prehistory. The Etruscans, Romans, Greeks, Indians, Chinese, Mexicans and

Japanese have all left evidence that they used hot waters in ancient times, where these waters were commonly thought to have healing properties. Since the 8th century A.D., the Japanese have used thermal waters for body purification, which is the first step in the purification of the spirit, and many hot spring sites have temples dedicated to the Buddha of Medicine. The Romans also used thermal springs for recreational purposes. They built spas all over the Mediterranean area, and to the furthest boundaries of their empire, for example at Bath in England, thus spreading their knowledge of the beneficial effects of thermal waters. The Roman poet Lucretius, who lived a few decades before Christ, mentions amongst natural phenomena the thermal springs of the Vesuvius region in Book VI (verses 747–748) of his poem *De Rerum Natura* (On the Nature of Things), and made the first attempt at giving a scientific explanation, rather than supernatural, of these natural phenomena. In the Middle Ages, Arabs and Turks developed and diffused the traditional use of thermal baths, later known as Turkish baths, whose rich and sensual atmosphere is masterly depicted by the French painter Ingres in his *The Turkish Bath* (1863, Louvre). These uses were to lead the way to the modern balneological industry.

Space heating with geothermal waters was, however, to come much later. Fridleifsson and Freeston, in their excellent paper on geothermal research and development [25], tell us that although primitive pipelines were built by the Romans and the Chinese to convey water and steam for baths, it was only when metal pipes and radiators became common that geothermal energy was used for space heating. Even in Iceland, where hot springs are abundant and the mean annual temperature is 4°C, and Reykjavik is at present the only capital city of the world heated entirely by geothermal energy, geothermal space heating was first installed in a house in 1909.

The earliest residential heating in the world by geothermal water was in Chaude Aigues (France) in the 14th century. The first municipal district heating system using geothermal water was set up in Reykjavik, Iceland, in 1930. At present, 90% of the total population of Iceland live in houses heated by geothermal water. Large-scale district heating systems using geothermal water have been built in many countries, such as France, Russia, Georgia, China, Italy, and the USA.

Geothermal waters were first used in greenhouse heating in Iceland in the 1920s, now hundreds of hectares of greenhouses are operating throughout the world. In the last two decades geothermal heat has been used on an increasingly large scale in animal husbandry, fish farming, crop drying and soil heating. Air conditioning using geothermal steam was first developed in a hotel in Rotorua, New Zealand, in the late 1960s.

Mineral extraction from geothermal fluids is recorded from Etruscan times, as documented by numerous archaeological finds, especially the fine ceramics whose glazes and paints contain traces of boric salts coming from the hot boric waters of that part of Tuscany known as the boraciferous region (Larderello). A prosperous boric acid industry, which lasted 150 years, was created in the Larderello area in 1818 extracting boric salts from the geothermal waters of the area. In Iceland geothermal fluids were used to extract salts from sea water in the 18th century, and in New Zealand a pulp and paper mill has been using more than 200 t/h of geothermal

steam for processing the wood since the early 1950s. In China geothermal water has been used for its chemical properties in large scale carpet dyeing.

Electricity generation from geothermal steam is a much more recent industry, dating back to the beginning of the last century. In fact, commercial generation of electricity from geothermal steam began in Larderello, Tuscany, Italy, in 1913, with an installed capacity of 250 kW_e. However, the first experiments to make use of natural steam to generate electricity date back to 1904, when Prince Piero Ginori Conti coupled a steam-engine to a dynamo to light five bulbs in his boric acid factories at Larderello. Since 1950 other countries have followed the Italian example, and at present electricity is generated from geothermal energy in 21 countries all over the world. The evolution in time of the world-wide geothermal installed electrical capacity is presented in Fig. 12.

It is now clear that geothermal utilisation is divided into two categories, i.e. *electric energy production* and *direct uses*. Figure 13 shows the minimum production temperatures generally required for the different types of utilisation. The upper and lower limits are, however, not stringent and serve only as guidelines. Conventional electric power production is limited to fluid temperatures above 150°C, but considerably lower temperatures can be used in binary cycle systems, also called organic Rankine cycles, (in this case the outlet temperatures of the geothermal fluid are commonly above 85°C). The ideal temperature of thermal waters for space heating is about 80°C, but larger radiators in the houses or the use of heat pumps or auxiliary boilers means that thermal water with temperatures only a few degrees above ambient temperature can be used beneficially [25].

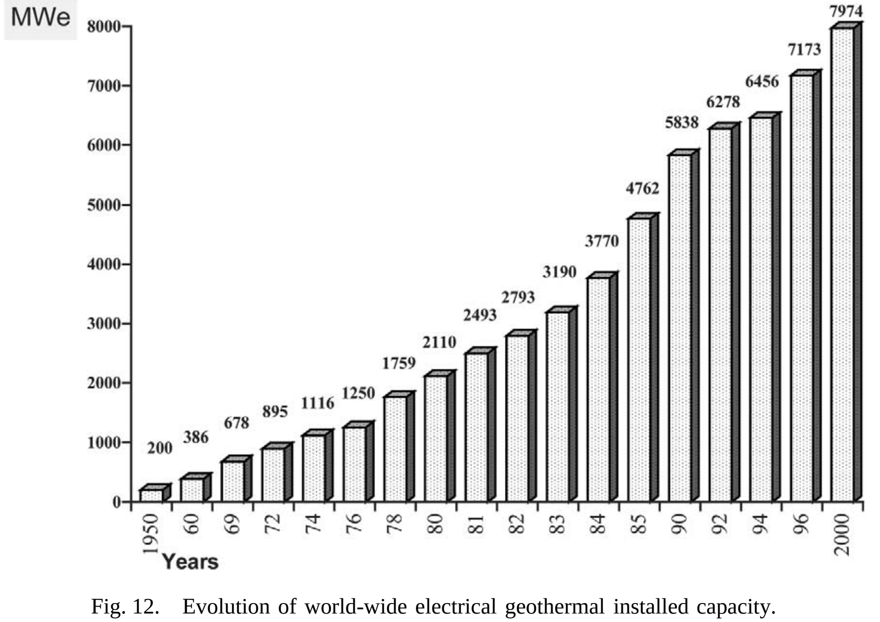


Fig. 12. Evolution of world-wide electrical geothermal installed capacity.

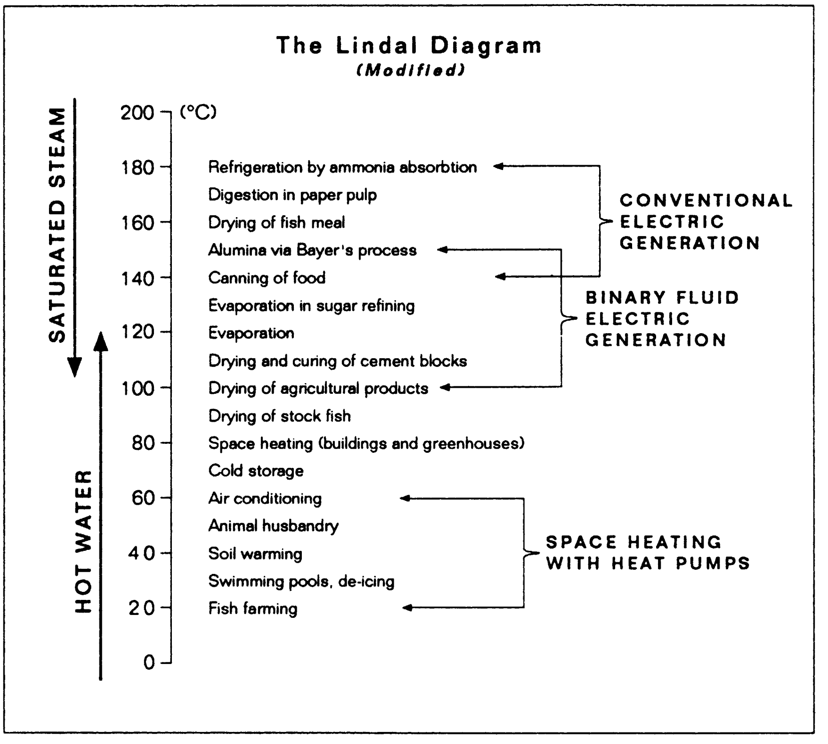


Fig. 13. The Lindal diagram on typical fluid temperatures for direct applications of geothermal resources. Source [25], modified.

9.2. Electricity from geothermal fluids

9.2.1. The world scenario

The world geothermal electrical capacity installed in the year 2000 was 7974 MW_e (Table 2) with the generation in that year of 49.3 billion kWh [26]. Since Gerald Huttrer compiled this table, further 282 MW_e have been installed, bringing the total to 8256 MW_e [27]. All figures of electrical capacity shown in this review refer to installed capacity. Efficient capacity is in some cases much smaller, but very little information is available in the international literature. Figure 12 shows the evolution of the world geothermal electrical capacity.

The total electricity produced world-wide from all sources in the year 1998 was 14,411 billion kWh (15,342 in 2000) [28] of which 2826 billion kWh were generated by renewable sources (2600 billions by hydropower alone, and 226 billions altogether by biomass, geothermal, wind, solar and tidal, [29]). These values show that renewables with the exception of hydro played a very minor role on the world energy scene in 1998 (and again in 2000), but geothermal ranked third after hydro and biomass (Tables 3 and 4).

The contribution of geothermal energy is entirely different if we distinguish

Table 2
Installed geothermal generating capacities in the world in the year 2000. Source [26]

Country	Installed MWe	GWh generated	% of national capacity	% of national energy
Australia	0.17	0.9	n/a	n/a
China	29.17	100	n/a	n/a
Costa Rica	142.5	592	7.77	10.21
El Salvador	161	800	15.39	20
Ethiopia	8.52	30.05	1.93	1.85
France	4.2	24.6	n/a	2
Guatemala	33.4	215.9	3.68	3.69
Iceland	170	1138	13.04	14.73
Indonesia	589.5	4575	3.04	5.12
Italy	785	4403	1.03	1.68
Japan	546.9	3532	0.23	0.36
Kenya	45	366.47	5.29	8.41
Mexico	755	5681	2.11	3.16
New Zealand	437	2268	5.11	6.08
Nicaragua	70	583	16.99	17.22
Philippines	1909	9181	n/a	21.52
Portugal	16	94	0.21	n/a
Russia	23	85	0.01	0.01
Thailand	0.3	1.8	n/a	n/a
Turkey	20.4	119.73	n/a	n/a
USA	2228	15,470	0.25	0.4
Totals	7974.06	49,261.45		

between industrialised and developing countries. In the *industrialised* countries, where the installed electrical capacity reaches very high figures (tens or even hundreds of thousands of MW_e), geothermal energy is unlikely, in the next decade, to account for more than one percent, at most, of the total [26].

In *developing* countries, with an as yet limited electrical consumption but good geothermal prospects, electrical energy of geothermal origin could, on the contrary, make quite a significant contribution to the total: at the moment, for instance, 21% of the electricity in the Philippines comes from geothermal sources, 20% in El Salvador, 17% in Nicaragua, 10% in Costa Rica and 8% in Kenya [26], Table 2. The geothermal electricity generation in different areas of the world in the year 2000 is reported in Table 5, [26].

9.2.2. *Efficiency of generation*

The efficiency of the generation of electricity from geothermal steam ranges from 10 to 17%, about three times lower than the efficiency of nuclear or fossil-fuelled plants. Geothermal plants have the lowest efficiency values due to the low temperature of the steam, which is generally below 250°C.

Furthermore, geothermal steam has a chemical composition that is different from pure water vapour, because it generally contains non-condensible gases (CO_2, H_2S,

Table 3
Electricity from renewable energies in the world. Source [29]

	Energy production in 1998		Operating capacity, end 1998		Capacity factor	Current energy cost	Potential future energy cost	Turnkey investment cost	Increase in inst. capac. last 5 years
	TWh_e	%	GW_e	%	%	US¢/kWh	US¢/kWh	US$/kW	%/year
Hydro *	2600	92	663	91.8	20–70	2–10	2–8	1000–4000	2
Biomass	160	5.66	40	5.53	25–80	5–15	4–10	900–3000	3
Geothermal	46	1.63	8	1.11	45–90	2–10	1–8	800–3000	4
Wind	18	0.64	10	1.38	20–30	5–13	3–10	1100–1700	30
Solar (photovoltaic)	0.5	0.05	0.5	0.12	8–20	25–125	5–25	5000–10000	30
(thermal electricity)	1		0.4		20–35	12–18	4–10	3000–4000	5
Tidal	0.6	0.02	0.3	0.04	20–30	8–15	8–15	1700–2500	0
Total	2826.1		722.2						

* Large hydro stations produce 2510 TWh (capacity 640 GW_e) and small 90 TWh (23 GW_e).

Table 4
Electricity from four renewable energy sources in 1998. Source [29]

	Operating capacity		Production per year	
	GW_e	%	TWh/a	%
Geothermal	8	41.7	46	69.6
	10	52.1	18	27.2
Wind	0.9	4.7	1.5	2.3
Solar	0.3	1.5	0.6	0.9
Tidal				
Total	19.2	100	66.1	100

Table 5
Electricity generation and direct use of geothermal energy in the year 2000 in various geographic areas of the world. Source [29]

	Electricity generation			Direct use		
		Total production			Total production	
	Installed capacity MW_e	GWh/a	%	Installed capacity MW_t	GWh/a	%
Africa	54	397	1	125	504	1
America	3390	23,342	47	4355	7270	14
Asia	3095	17,510	35	4608	24,235	46
Europe	998	5745	12	5714	18,905	35
Oceania	437	2269	5	342	2065	4
Total	7974	49,263	100	15,144	52,979*	100

* Asia direct use was modified to include baths in Japan

NH_3, CH_4, N_2 and H_2) that have to be extracted from the condensers of power plants. These gases are present in the steam in variable quantities (1–50 g/kg of fluid) and they reduce the efficiency of electricity generation.

Geothermal power plants require from 6 kg/kWh (if dry steam is available) to 400 kg/kWh of fluid (if hot water is used in binary cycle plants), the latter referring to electricity generated from low-to-medium temperature resources (85–150°C).

9.2.3. Electricity generating cycles

The simplest and cheapest of the geothermal cycles used to generate electricity is the *direct-intake non-condensing* cycle. Steam from the geothermal well is simply passed through a turbine and exhausted to the atmosphere: there are no condensers

at the outlet of the turbine (Fig. 14). Such cycles consume about 15–25 kg of steam per kWh generated. Non-condensing systems must be used if the content of non-condensible gases in the steam is very high (greater than 50% in weight), and will generally be used in preference to the condensing cycles for gas contents exceeding 15%, because of the high power that would be required to extract these gases from the condenser.

Condensing plants, with condensers at the outlet of the turbine and conventional cooling towers (Figs. 14 and 15), show a much lower consumption, only 6–10 kg of steam per kWh generated, but the gas content of the steam must be less than 15%. The specific consumption of steam of these units is greatly influenced by the turbine inlet pressure: for pressures ranging from 15 to 20 bar (1.5–2.0 MPa), the consumption is close to 6 kg/kWh. For pressures ranging from 5 to 15 bar (0.5–1.5 MPa) the consumption is from 9 to 7 kg/kWh, and it becomes much greater for even lower pressures [30].

In power plants where electricity is produced from dry or superheated steam (vapour-dominated reservoirs), steam is piped directly from the wells to the steam turbine. This is a well developed, commercially available technology, with typical turbine-size units in the 20–120 MW_e capacity range. Recently, a new trend of installing modular standard generating units of 20 MW_e has been adopted (Italy).

Vapour-dominated systems are less common in the world, steam from these fields has the highest enthalpy (energy content), generally close to 670 kcal/kg (2800 kJ/kg). At present these systems have been found only in Indonesia, Italy, Japan and the USA. These fields produce about half of the geothermal electrical energy of the world. Water-dominated fields are much more common. Flash steam plants are used to produce energy from these fields that are not hot enough to flash a large proportion of the water to steam in surface equipment, either at one or two pressure stages.

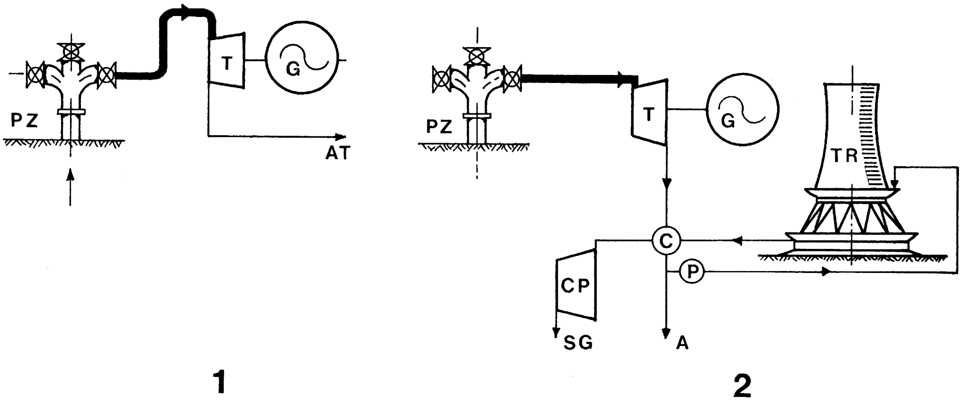


Fig. 14. Geothermal cycles for generation of electricity. 1) Direct-intake exhausting-to-atmosphere turbine. 2) Direct-intake condensation turbine and cooling tower. PZ, geothermal well; T, turbine; G, generator; AT, exhaust to atmosphere; CP, compressor-extractor of non-condensible gases contained in the geothermal fluid; SG, gas discharge; C, condenser; P, pump; A, water discharge; TR, cooling tower. Source [44].



Fig. 15. The 120 MW_e power plant Valle Secolo at Larderello, Tuscany, Italy.

Commercially available turbogenerators units are commonly in the range 10–55 MW_e. Modular standardised units of 20 MW_e are being implemented.

If the geothermal well produces hot water instead of steam, electricity can still be generated, provided the water temperature is above 85°C, by means of *binary cycle plants*. These plants operate with a secondary, low boiling-point working fluid (freon, isobutane, ammonia, etc.) in a thermodynamic cycle known as the organic Rankine cycle. The working fluid is vaporised by the geothermal heat in the vaporiser. The vapour expands as it passes through the organic vapour turbine, which is coupled to the generator. The exhaust vapour is subsequently condensed in a water-cooled condenser or air cooler and is recycled to the vaporiser by the motive fluid cycle pump (Fig. 16). The efficiency of these cycles is even lower: between 2.8 and 5.5%. Typical unit size is 1 to 3 MW_e. However, the binary power plant technology has emerged as the most cost-effective and reliable way to convert large amounts of low temperature geothermal resources into electricity, and it is now well known that large low-temperature reservoirs exist at accessible depths almost anywhere in the world.

The power rating of geothermal turbine/generator units tends to be smaller than in conventional thermal power stations. Most commonly the units are 55, 30, 15, 5 MW_e or smaller. One of the advantages of geothermal power plants is that they can be built economically in relatively much smaller units than, for example, hydropower stations. In developing countries with a small electricity market, geothermal power plants with units from 15 to 30 MW_e can thus be more easily adjusted to the annual increase in electricity demand than, say, 100 or 200 MW_e hydropower plants. The reliability of geothermal power plants is very good, the annual load factor and avail-



Fig. 16. Ormat geothermal binary power plant exploiting hot water, 30 MW_e, East Mesa, California (Courtesy of Ormat, USA).

ability factor are commonly about 90%, and geothermal fields are not affected, for example, by annual or monthly fluctuations in rainfall, since the essentially meteoric water has a long residence time in geothermal reservoirs [25].

9.2.4. Cost of electricity generation

In geothermal development for the generation of electricity, about 50% of total costs are related to the identification and characterisation of reservoirs and, above all, to the drilling of production and reinjection wells. Of the remainder, 40% goes to power plants and pipelines, and 10% to other activities.

The cost of the geothermal kWh (2–10 US cents) is characterised by a high share of capital cost (steamfield and plants), and relatively low operation and maintenance costs. The investment share in the cost of the geothermal kWh is due to the following activities:

- the surface exploration and the surveys preliminary to deep drilling aimed at identifying the possible existence of a geothermal field;
- the drilling of exploration, production, and reinjection wells (including non-productive wells): the first are necessary for the characterisation of the fluid and the field, while the others serve for its exploitation and development;
- the construction of surface installations: steam pipelines, water pipelines, fluid treatment installations and power plants.

The cost of realising a generating geothermal plant may vary, on average, from 800 to 3000 US$ per installed kW, all costs included. The most likely investment cost for a 40 MW_e power plant in a known geothermal field is 51 million US$, with a range 1062–1692 US$ per installed kW [48].

Table 3 compares electricity production costs (installed kW and cost of kWh) of renewables.

9.3. Non-electrical uses of geothermal energy

9.3.1. The world scenario

The utilisation of natural steam for electricity generation is not the only possible application of geothermal energy. Hot waters, that appear to be present in large parts of all the continents can also be exploited and offer interesting prospects, especially in space heating and industrial processes [53]. The distribution of the thermal energy used by category is approximately [31]:

- 42% for bathing and swimming pool heating;
- 23 % for space heating;
- 12% for geothermal heat pumps (groundwater heat pumps);
- 9% for greenhouse heating;
- 6% for fish farm pond;
- 5% for industrial applications;
- 2% for other uses and
- less than 1% for agricultural drying, snow melting and air conditioning.

The thermal power installed for non-electrical uses of geothermal energy worldwide in the year 2000 has been estimated at 15,144 MW_t, distributed among 58 countries [31], Tables 5 and 6. These applications utilise a total of 52,746 kg/s of fluid (190,000 t/h), contributing to a savings of about 13 million tons of oil per year. The load factor is influenced by a number of things, including local climate, process use and commercial interests. Heat pumps utilising very low-temperature fluids

Table 6
Direct heat production from renewables. Source [29]

	Energy production in 1998 TWh_t	Operating capacity end 1998 GW_t	Capacity factor %	Current energy cost US¢/ kWh	Potential future energy cost US¢/ kWh	Turnkey investment cost US$/kW	Increase in inst. capac. last 5years%/ year
Biomass	>700	>200	25–80	1–5	1–5	250–750	3
Geothermal	40	11	20–70	0.5–5	0.5–5	200–2000	6
Solar heat low temp.	14	18	8–20	3–20	2–10	500–1700	8

(<50°C) have extended geothermal developments into traditionally non-geothermal countries such as France, Switzerland, Germany and Sweden, as well as areas of the mid-western and eastern United States. Most equipment used in these projects is of standard, off-the-shelf design and need only slight modifications to handle geothermal fluids. Ground-coupled and groundwater heat pump installations use the ground or the groundwater as the heat source during the winter heating operations, and as the heat sink during the summer cooling operation. An estimated 500,000 ground-coupled heat pumps are operating in private and public sectors in 26 countries. Table 7 shows the world's top countries using geothermal energy in direct uses [29].

9.3.2. Economic constraints and need of promotion

In geothermal fluid utilisations the time lapse between the discovery of a resource and its exploitation is reasonably short if electricity generation is possible, but still very lengthy if hot water is the only final result. It is still difficult to convince governments and investors that non-electrical uses of geothermal energy can play a significant role in the saving of high quality fuels. The financial side of these operations is, in fact, still a major constraint in the use of natural hot water: the economic benefits generally come only after a long time, and, worse still, large investments are required from the very beginning of a project. However, in many cases the utilisation of geothermal waters in non-electrical applications can be a viable and economic option in the right conditions, especially if fossil fuels must be imported, and an advantage for the environment avoiding the release of combustion gases into the atmosphere.

Table 7
World's top countries using geothermal in direct uses. Source [29]

	Installed MW_t	Production GWh/a
China	2282	10531
Japan	1167	7482
USA	3766	5640
Iceland	1469	5603
Turkey	820	4377
New Zealand	308	1967
Georgia	250	1752
Russia	308	1707
France	326	1360
Sweden	377	1147
Hungary	473	1135
Mexico	164	1089
Italy	326	1048
Romania	152	797
Switzerland	547	663

9.4. Economics of geothermal development

Geothermal development is a consequence of a group of closely interrelated activities which include earth science and engineering technologies. Earth science activities predominate during the fluid recovery phase of a project, whereas the engineering technologies prevail during the utilisation phase. The first step is to conduct surveys of moderate cost that will provide the operators with a rapid assessment of large areas of territory and permit to select, within this territory, the most promising areas. Specifically, more expensive investigations can then be carried out in these areas to identify one or more favourable sites for deep exploratory drilling. Exploratory drilling and well testing represent therefore the next stage of the project, the cost of this stage is higher than that of the preceding surveys since drilling is cost-intensive. The project will end with field development and exploitation, which, in addition to further drilling, entail reservoir engineering studies and the construction of surface plants and equipment. These activities are also cost-intensive.

The initial phase of selecting the most favourable area(s) is usually called geothermal *reconnaissance*. The surface investigations in the selected area(s) form the *pre-feasibility* phase, while the subsequent *feasibility* phase consists of deep exploratory drilling and reservoir testing. The final phases of the project are those of *development* and *exploitation*.

10. Investments in geothermal electrical and non-electrical uses world-wide

Geothermal energy has long been a well-proven energy resource that uses mostly conventional technology. Commercial generation of electricity started in 1913 and installed capacities of hundreds of megawatts, both for electrical and non-electrical uses (direct uses), had already been installed half a century ago.

Comprehensive surveys have been carried out on many geothermal issues, but until 1994 there had been no exhaustive analysis of geothermal investments world-wide. In that year, Fridleifsson and Freeston [25] made a survey of investment data from all the main geothermal countries in the world between 1973 and 1992. The survey indicates the total investments to be around 22,000 million US$, 7600 of which were invested during 1973–1982 and 14,300 during 1983-1992, indicating an increase in total investments of 89%. More specifically, 17,600 million US$ (80%) were invested in industrialised countries, 3500 million (16%) in developing countries, and 800 million (4%) in Eastern European countries.

The types of investments in geothermal research and development are in many ways similar to those for oil and gas, i.e. technological research and development, geothermal exploration (through geological, geophysical and geochemical surveys), drilling, field development, power plants or plants for non-electrical uses. Geothermal projects are more site-specific than oil and gas projects as geothermal fluids are normally used at the geothermal field, or fairly close to it. This link to the production area is not related to technological difficulties in transporting hot water or steam over distances of tens of kilometres, but to the cost of insulating the pipelines to

avoid heat losses. It would be uneconomical for the modest energy content of the geothermal resource to be moved over long distances. In fact, whereas burning a kilogram of oil produces 10,000 kilocalories (41,800 kJ), one kilogram of the best geothermal steam will produce at most 700 kcal (3000 kJ), and one kilogram of hot water operating between 80°C (production temperature) and 30°C (discharge temperature) will yield only 50 kcal (209 kJ).

Concluding, it is clear that the level of investments in geothermal plants will be significantly affected by the evolution of oil and other energy prices. The introduction of a pollution tax for the emission of CO_2 and sulfur, as recently discussed internationally, would significantly improve the economic competitiveness of geothermal energy with respect to fossil fuels (natural gas excluded) (Fig. 17). The European Union proposal of US$0.10 per kg of carbon, equivalent to cents of US$ 2.7/kg of

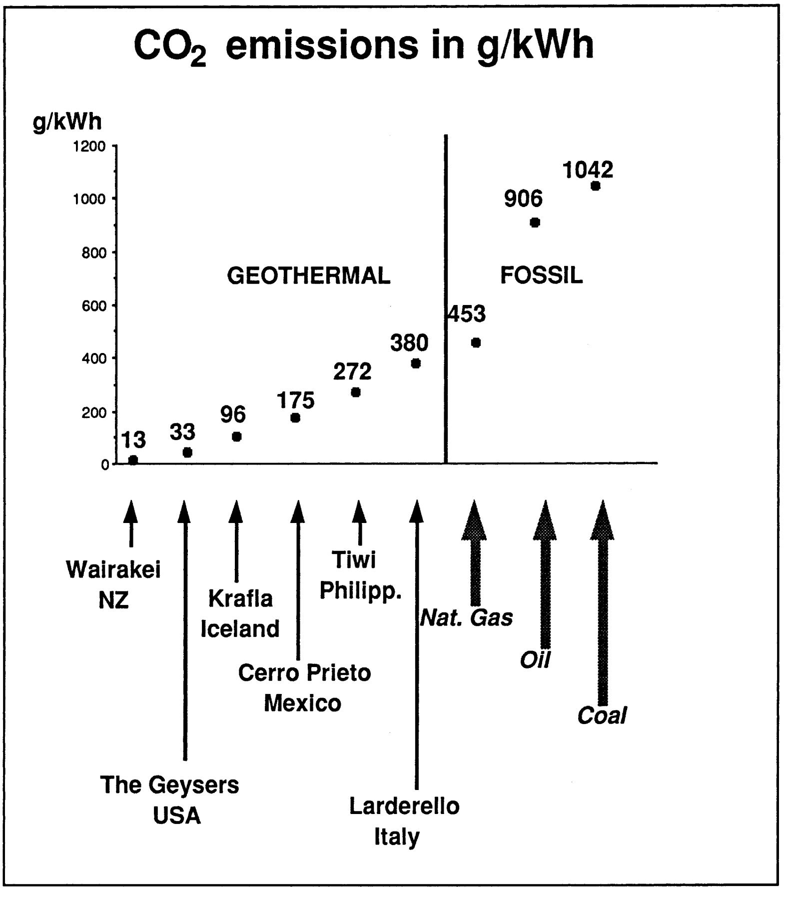


Fig. 17. Comparison of carbon dioxide emissions from geothermal and fossil fuel-fired power plants. Source [44].

CO_2 would be a reasonable starting point. Geothermal emissions of carbon dioxide are in the range of 0.01–0.4 kg/kWh, compared to 0.5–1.1 kg/kWh of carbon dioxide from fossil fuels. The carbon tax would hit geothermal power generation with an extra charge between 0.04 and 1 cent/kWh, compared to 1.2–2.8 for fossil fuel generation [32].

11. Environmental impact of geothermal energy and social acceptability

11.1. The environmental impact

Utilisation of geothermal heat entails the extraction of large volumes of steam, or steam and water (for example, 8000 t/h at The Geysers field in California, now producing 1036 MW_e only, and 3000 t/h at Larderello, Italy, 547 MW_e installed).

Geothermal fluids have a chemical content that is site-specific, and highly dependent on the rocks of each reservoir. The major environmental impact of geothermal exploitation is pollution of air and bodies of water (rivers and lakes).

11.1.1. Air pollution

Steam from major geothermal fields has a content of non-condensible gases (CO_2, H_2S, NH_3, CH_4, N_2 and H_2) that ranges from 1.0 to 50 g/kg of steam. *Carbon dioxide* is the major component, but its emission into the atmosphere is well below the figures for natural gas, oil or coal-fired power stations per kWh generated (Fig. 17).

Hydrogen sulfide is the air pollutant of major concern in geothermal development. Its emissions generally range between 0.5 and 6.8 g/kWh. H_2S is oxidised to sulfur dioxide and then to sulfuric acid, and may cause acid rain. However a direct link between H_2S emission and acid rain has not been established. Without abatement, the specific emissions of sulfur from geothermal power plants are about half of those from coal-fired plants (Fig. 18).

Geothermal plants do not emit nitrogen oxides, fossil fuel plants on the contrary exhaust these toxic chemicals.

Geothermal gases in steam may also contain ammonia (NH_3), traces of mercury, (Hg), boron vapours (B), hydrocarbons such as methane (CH_4), and radon (Rn).

Boron, ammonia, and to a lesser extent mercury, are leached from the atmosphere by rain, leading to soil and vegetation contamination. Boron, in particular, can have a serious impact on vegetation. These contaminants can also affect surface waters and impact aquatic life. Geothermal literature reports that mercury emissions from geothermal power plants range between 45 and 900 micrograms/kWh, and are comparable with mercury emissions from coal-fired power plants. Ammonia is discharged into the atmosphere in concentrations between 57 and 1938 mg/kWh, but due to atmospheric processes it is dispersed rapidly.

Radon (^{222}Rn), a gaseous radioactive isotope naturally present in the Earth's crust, is contained in the steam and discharged into the atmosphere in concentrations of 3700–78,000 Becquerel/kWh [33]. At Larderello geothermal field (Italy) radon concentration in air at ground level is 5.5 Bq/m^3 [34], at The Geysers (California) ranges

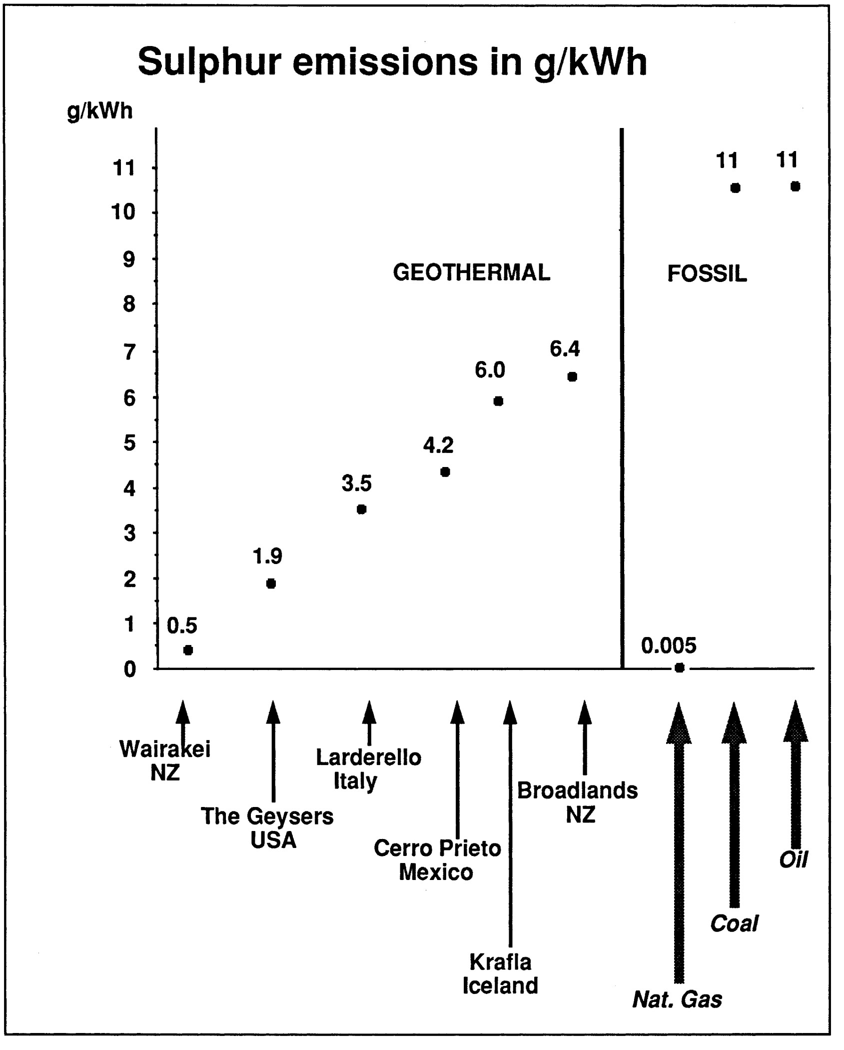


Fig. 18. Comparison of sulfur emissions from geothermal and fossil fuel-fired power plants. Source [44].

from traces to 6.0 Bq/m^3. By comparison, average levels of radon in air elsewhere are around 3 Bq/m^3. Although its levels should be monitored, there is little evidence that radon concentrations are raised above background level by geothermal emissions.

Binary plants, in which the geothermal fluid is passed through a heat exchanger and reinjected without exposure to the atmosphere, will not discharge either gas or fluid to the environment during normal operation.

11.1.2. Water pollution

Water pollution of rivers and lakes is a potential hazard in power production and the management of spent geothermal fluids.

In *vapour-dominated* reservoirs, most of the pollutants are found in the vapour state, and the pollution of water bodies is more easily controlled than in water-dominated reservoirs. In the latter waste steam condensate (20% of the steam supply) must be added to the waste water. The water and the condensate generally carry a variety of toxic chemicals in suspension and solution: arsenic, mercury, lead, zinc, boron and sulfur, together with significant amounts of carbonates, silica, sulfates and chlorides.

In *water-dominated* and in *hot water* reservoirs, water and steam (if present) are separated at the surface (the steam is used for the generation of electricity), and the volume of water to be disposed of (which may contain large quantities of salts, even above 300 g/kg of extracted fluid) can be as much as 70 kg/kWh, more than four times the steam supply, and up to 400 kg/kWh in binary cycle plants.

Reinjection through wells drilled into selected parts of the geothermal reservoir is the most common method of disposal. Reinjection may also help to maintain reservoir pressure, to extract additional heat from the rock, and to prolong the useful life of the resource.

Reinjection might seem at first sight to be quite expensive, as it involves further wells, surface piping and continuous pumping, but the long-term effects are very beneficial. Calculated over the entire lifetime of a geothermal project, reinjection is normally less expensive than no reinjection [25].

11.1.3. Land subsidence

The weight of the rocks above a reservoir of groundwater, oil or geothermal fluids is borne in part by the mineral skeleton of the reservoir rock, and in part by fluids in the rock pores. As fluids are removed, pore pressure is reduced, and the ground tends to subside. Less subsidence is expected with harder reservoir rock.

The scale of geothermal fluid extraction is comparable to large agricultural groundwater withdrawals. A potential for subsidence is associated with geothermal development.

Water-dominated fields subside *more* than vapour-dominated fields. For example, the Wairakei water-dominated geothermal field in New Zealand (157 MW_e) showed 4.5 m of localised subsidence between 1964 and 1974, with the extraction of 622 Mtons of fluid, and the maximum amount of 14 m from 1950 to 1998 [35]. The Geysers vapour-dominated field in California (now 1036 MW_e) subsided 0.14 m between 1973 and 1977, and Larderello (Tuscany) also a vapour-dominated field, subsided 1.7 m between 1923 and 1986 [36].

Subsidence can be controlled or prevented by the reinjection of spent fluids. Reinjection could, however, induce microseismicity.

11.1.4. Induced seismicity

We have seen in earlier sections that many geothermal reservoirs, especially at high-temperature, are located in geologically unstable zones of the Earth's crust.

These are zones characterised by volcanic activity, deep earthquakes, and a heat flow that is higher than the average. They are also zones with a higher frequency of naturally occurring seismic events. Water reinjection into the reservoir may induce further seismic activity by reducing rock stress, loosening vertical faults, and triggering the release of accumulated tectonic stress.

A study of the correlation between seismicity and water reinjected into the wells within a geothermal area (Larderello, Italy) suggests that a percentage of low-magnitude events are induced. However, the data also indicate that an increase in the quantity of injected water does not produce an increase in the maximum value of the magnitude of the events, but only of their number. Reinjection of waste fluids might therefore even have a positive effect, triggering a higher number of low intensity shocks, but favouring the progressive, non instantaneous release of the stress accumulated in the rocks.

11.1.5. Noise

Wells newly drilled or during maintenance have a noise level of 90–122 dB at free discharge, and 75–90 dB through silencers [37].The pain threshold is 120 dB at 2000–4000 Hz. By comparison, a jet takeoff is 125 dB at 60 m.

11.2. The social acceptability of geothermal energy

In recent years, when planning initiatives of great interest, or when discussing the opportunity of starting a development project in a given area, the issue of "social acceptability" of the project has come to the fore for policy-makers, investors, local administrators and common people living in the area concerned [38]. The debate on these issues is usually lively in case of important industrial projects, but it may become very lively in the case of large geothermal developments due to their impact on relatively small areas.

Social acceptability depends on the political, economic and social circumstances of the community, and is attained if the activities related to the project do not result in drastic changes of the normal conditions of the area, and if the affected sectors can see some advantages in adjusting their lifestyle, and in modifying some practices to attain the new benefits arising from the project [39]. However, to achieve no pollution or no public concern at all would also mean to abandon any economic activity. Cataldi [38] has proposed the following definition of social acceptability: "*Social acceptability of a geothermal project is the condition upon which the technical and economic objectives of the project may be pursued in due time, with the adhesion of the local communities, obtained by acting in consonance with the dynamic conditions of the environment and in the respect of the people's health, welfare and culture*".

As a consequence, social acceptability of a project is a necessary condition of any geothermal development, and as such it will represent a component of the project's cost. An evaluation of environmental impact will be prepared in advance and public information should start in the project area as soon as possible.

12. Advanced geothermal technologies for the future

12.1. Hot Dry Rock systems

Hot Dry Rock (HDR) geothermal reservoirs differ significantly from conventional geothermal reservoirs, which probably exist only in the geologically favoured regions of the world shown in Fig. 3. In these regions, nature provides not only the hot rock, but also the hot water or steam.

HDR reservoirs are, instead, man-made reservoirs in rocks that are artificially fractured, and thus any convenient volume of hot dry rock in the earth's crust, at accessible depth, can become an artificial reservoir (Fig. 19).

A pair of wells is drilled into the rock, terminating several hundred meters apart. Water is circulated down the injection well and through the HDR reservoir, which acts as a heat exchanger. The fluid then returns to the surface through the production well, and thus transfers the heat to the surface as steam or hot water. Experts agree that the following key parameters, representing the lower end of the range for each, are required for a commercially-viable HDR reservoir: production flow rate 50–75 kg/s; effective heat transfer area $>$2 million square meters; rock volume accessed $>$200 million cubic meters; flow losses (% of injection flow) $<$10% [40].

A pioneer HDR project at Los Alamos, New Mexico, USA has now reached the threshold of economic viability at a cost of US$175 million (1993). Since then, field experiments of various magnitudes have been undertaken in the United Kingdom, France, Germany and Japan and, more recently, in Sweden and Australia. These experiments have been concerned with the validation of various concepts of HDR exploration.

HDR systems, or better the enhancement of low-permeability fracture systems in high temperature rocks on the margins of productive geothermal fields (HWR, Hot Wet Rock systems), could however represent the new frontier, as there are comparatively few locations on the Earth's crust that have natural hydrothermal systems similar to those exploited at present, where heat, reservoir and fluid are together all provided by nature. The HWR systems fill the gap between HDR and hydrothermal systems [41]. New stimulation projects of this type exploit the techniques developed in the HDR experiments. Reservoir stimulation entails the creation of permeable paths by artificial techniques. Stimulation is generally related to a restoration of permeability to its original state or to the enhancement of the flow area in the rock around the well by creating highly conductive fractures. The most common stimulation techniques are hydraulic fracturing, chemical fracturing and explosive fracturing. These projecs have been launched in Japan, with the purpose of stimulating low-permeability hydrothermal systems at temperatures up to 250°C and at depths between 1800 and 2200 m. Similar projects could also be developed in areas of low permeability, low pressure (60–70 bar, 6–7 MPa), but very high temperatures (350–400°C), at 3500 m depth in the Larderello area, Tuscany. Reservoir stimulation techniques applied to wells in these areas could increase the profitability of the field increasing its productivity. It is assumed that these dry wells exist where flow-paths are restricted and permeability is of the order of a few millidarcies or less.

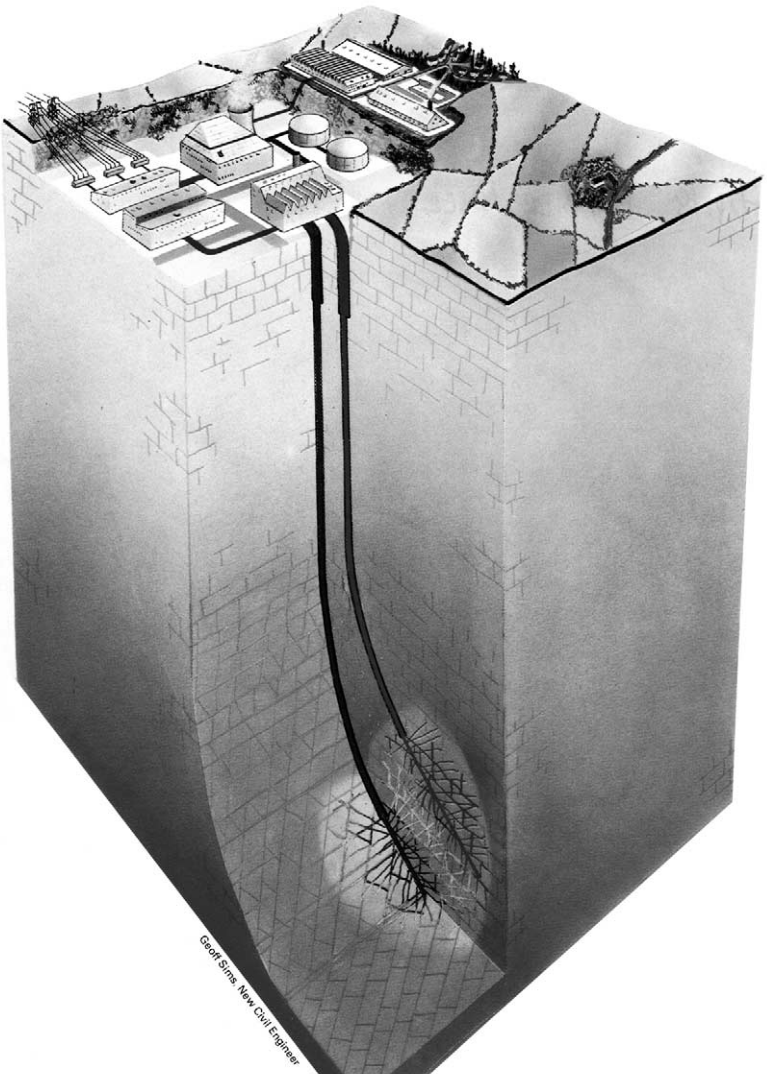


Fig. 19. Schematic representation of a hot dry rock (HDR) reservoir formed by artificial fracturing. Water is circulated down the injection well, through the HDR reservoir, and then returns to the surface through the production well as steam or hot water. Source [46].

12.1.1. Economics of HDR/HWR systems

At present, the breakthrough and advance of HDR technology in the energy industry is being slowed down by two factors:

- First, there is a lack of experience in building and operation of commercial plants

so the technology still remains in an experimental phase. A single successfully operating HDR/HWR plant demonstrating economic sustainability would be a distinct advantage.
- Secondly, the low price of fossil fuels does not encourage any but the more far-sighted members of the energy industry to undertake adventurous sorties into new technologies requiring high up-front investments.

The advantages of HDR/HWR lie first of all in its large potential and accessibility over large regions of the Earth's surface and, secondly, in the environmentally benign nature of the technology [42].

12.2. Magma energy

The thermal energy stored in magma bodies represents a huge potential resource. The goal of the US Magma Energy Extraction Program was to determine the engineering feasibility of locating, accessing, and utilising magma as a viable energy resource. Research is also at present carried out in Japan [47].

Realisation of this objective would require progress in four critical areas. These are:

- magma location and definition: crustal magma bodies must be located and defined in enough detail to position the drilling rig;
- drilling: high-temperature drilling and completion technology require development for entry into magma;
- materials: engineering materials need to be selected and tested for compatibility with the magmatic environment;
- energy extraction: heat extraction technology needs to be developed to produce energy extraction rates sufficient to justify the cost of drilling wells into the magma bodies [43].

12.3. Geopressured reservoirs

Geopressured reservoirs are deep reservoirs (4–6 km) in large sedimentary basins containing pressurised hot water that remained trapped at the time of deposition of the sediment, and at pressures of up to 100% in excess of the hydrostatic pressure corresponding to that depth.

Geopressured fields could produce not only the thermal energy of the pressurised hot water, but also hydraulic energy, by virtue of the very high pressure, and methane gas. These three energy forms can also be converted to higher value forms of energy using available technologies. Thermal energy can be converted to electricity in a geothermal turbine. Hydraulic energy can be converted to electricity using a hydraulic turbine. Dissolved methane gas can be separated and sold, burned, compressed, liquefied, converted to methanol, or converted to electricity by fuelling a turbine.

Geopressured resources have been investigated extensively in offshore wells in

Texas and Louisiana in the US Gulf Coast area (deepest well 6567 m), and pilot projects were operated there for some years to produce geopressured fluid and extract its heat and methane gas content. Also the Pannonian Basin in Hungary is at present under evaluation.

Electrical energy conversion experiments started in the US, but research has still to confirm the economic feasibility and long-term use of this resource.

13. Training of specialists, geothermal literature, and geothermal associations

13.1. Training of specialists

In 1968 it was already clear that one of the reasons for the slow progress of geothermal research, especially in developing countries, was the lack of qualified technical and scientific personnel. During that year UNESCO convened a group of experts to evaluate what steps could be taken to change this situation. The result of this action was the creation in 1970 of the first two geothermal training centres, one in Pisa, Italy, organised by the International Institute for Geothermal Research and financed by the Italian Ministry for Foreign Affairs and UNESCO, and the other in Kyushu, Japan, at the Research Institute of Industrial Science of the university, financed by the Japanese government and UNESCO. Two more training centres followed, both in 1979, one in Auckland, New Zealand, sponsored by the New Zealand government and the United Nations Development Project, and organised by the local university, and the other in Reykjavik, Iceland, a joint effort of the United Nations University and the Icelandic government.

Apart from these four centres, all operating with UN support, the Universidad Autonoma de Baja California (Mexico), in collaboration with the Comisión Federal de Electricidad and the Instituto de Investigaciones Eléctricas (both of Mexico), has been offering a full year training course in geothermal energy since 1984. Well-known and appreciated short courses are also organised regularly by the Geothermal Resources Council in the USA.

Approximately 1300 specialists have been trained in the UN-sponsored courses over the last quarter of the century, and the steady rise in the geothermal installed capacity, especially in the developing countries, is a clear proof of the validity of these training initiatives.

13.2. Technical information exchange

13.2.1. Journals

There is a large number of geothermal publications available, in the form of conference proceedings, journals and textbooks. Newcomers to geothermal activity may be disoriented by the mass of literature in circulation, estimated at about 30,000 titles since the beginning of last century.

Table 8 lists the journals that publish only geothermal material.

Table 8.
Journals that publish *only* geothermal articles. Source [44], modified

Geothermics	Specialised	Elsevier, UK	http://www.elsevier.com/locate/geothermics
Geotermia — Revista Mexicana de Geoenergia	Specialised	Comision Fed. de Electricidad, Mexico	e-mail: geoexplo@mich1.telmex.net.mx
Chinetsu-Journal of Japan Geoth. Energy Association	Specialised	Japan Geoth. Energy Assoc., Japan	http://www.nedo.go.jp/chinetsu/index.htm
Journal of the Geothermal Research Society of Japan	Specialised	Geothermal Research Society, Japan	http://wwwsoc.nii.ac.jp/grsj/toukou-e.html
Geothermal Resources Council Bulletin	General-News	Geothermal Resources Council, USA	http://www.geothermal.org
Geo-Heat Center Quarterly Bulletin	Technological	Oregon Institute of Technology, USA	http://geoheat.oit.edu
Geothermie	Newsletter	Schweiz. Vereinigung fuer Geothermie, Switzerland	e-mail: interprax@bluewin.ch
Geothermische Energie	Newsletter	Geothermische Vereinigung, Germany	http://www.geothermie.de
IGA News	Newsletter	International Geothermal Association, New Zealand	http://iga.igg.cnr.it

13.2.2. Gray literature

Various scientific organisations also publish, albeit irregularly, series of reports that are totally or partly dedicated to geothermal topics. The most important geothermal report series are those published in the USA by:

- Lawrence Berkeley National Laboratory, California,
- Sandia National Laboratory, New Mexico, and
- US Geological Survey, with their *Professional Papers*.

Further important recent sources of geothermal information are also:

- *Proceedings of the World Geothermal Congress '95* (5 volumes, 535 papers, 3028 pages), International Geothermal Association, Secretariat, c/o Enel Green Power, 120 Via Andrea Pisano, 56122 Pisa, Italy, tel. +39 050 535891; fax +39 050 535893; e-mail: igasec@enel.it
- *Proceedings of the World Geothermal Congress 2000* (670 papers on CD Rom), International Geothermal Association Secretariat, c/o Enel Green Power, 120 Via Andrea Pisano, 56122 Pisa, Italy, tel. +39 050 535891; fax +39 050 535893; e-mail: igasec@enel.it
- *Proceedings of the Annual Meetings* of the Geothermal Resources Council, GRC Transactions, fax +1-916-7582839; e-mail: grc@geothermal.org; web: www.geothermal.org
- *Proceedings of the Geothermal Reservoir Engineering Workshops*, Dept. of Pet-

roleum Engineering, Stanford University, California, fax +1-415-7252099; e-mail: shaun@pangea.stanford.edu
- *Proceedings of the European Geothermal Conference Basel '99*. Centre d'Hydrogeologie – Université de Neuchatel, Switzerland, 2 vols, 492 & 278 pp.; e-mail: francois.vuataz@chyn.unine.ch
- *Proceedings of the New Zealand Geothermal Workshops*, Geothermal Institute, University of Auckland, New Zealand, fax: +64-9-3737419; e-mail: thermal@auckland.ac.nz and
- *The World Directory of Renewable Energy: Suppliers and Services 2000*, James & James Science Publishers, London; fax +44-207387-8998; e-mail: orders@jxj.com; web: www.jxj.com

Amongst *books*, useful sources of information are [6][13][49][52][53][54][55].

13.2.3. Internet

Useful geothermal on-line systems are also:

- *International Geothermal Association* (IGA), at: http://iga.ig.cnr.it
- *IGA Discussion Group*, at: (e-mail) iga-group@geoscience.co.uk
- *Geothermal Education Office*, at: http://geothermal.marin.org/
- *Geothermal Resources Council On-line Information System* (USA), at: http://www.geothermal.org
- *Renewable Energy Database*, at: http://www.osti.gov/html/
- *THERMIE-European Union Energy Technology Program*, at http://www.ib.be/thermie
- *US Dept. of Energy Geothermal*, at: http://www.eren.doe.gov/geothermal/
- *World Bank*, at: http://www.worldbank.org/html/fpd/energy/geothermal/
- *WREN-World Renewable Energy*, at: http://www.wrenuk.co.uk

13.2.4. National and international geothermal associations

Local initiative in some countries has led to the creation of national geothermal associations with the general objective of encouraging research, exploration and development of geothermal energy.

The largest and best known of these *national* geothermal associations is the *Geothermal Resources Council*, an educational association based in Davis, California, and founded in 1972. Other, younger national associations have emerged in Canada, China, Georgia, Germany, Hungary, Indonesia, Italy, Japan, Lithuania, Mexico, New Zealand, Poland, Romania, Russia, Slovakia, Switzerland, Turkey. In the USA, apart from the Geothermal Resources Council, there are associations devoted to the development of specific tasks or local geothermal resources. Japan has also the Geothermal Research Society of Japan, based at the Geological Survey of Japan in Tsukuba.

The *International Geothermal Association* (IGA) was created in 1988 by the joint efforts of a group of geothermal experts from a number of countries.The International Geothermal Association is:

- a broad, open forum for the discussion and debate of problems of common interest,

- a focus for the evaluation of actions and means necessary to strengthen the human capabilities needed for accelerated research, development and application of geothermal resources,
- a vehicle for the encouragement and implementation of activities necessary to accelerate the utilisation of geothermal resources around the world, and
- a reference point for geothermal-related activities in which the international geothermal community is involved.

The IGA can be contacted at: International Geothermal Association, Secretariat, c/o Enel Green Power, 120 Via Andrea Pisano, 56122 Pisa, Italy, tel. +39 050 535891; fax +39 050 535893; e-mail: igasec@enel.it http://iga.igg.cnr.it

14. Conclusions

The utilisation of geothermal resources, that is, of the Earth's internal heat, is probably as old as mankind itself. However, only at the beginning of 1900, did we begin to understand the geothermal phenomenon, and why it occurs in certain areas.

It is probably evident from this report that the search for and the use of the Earth's heat, especially on an industrial scale, is a multidisciplinary activity, implying the interaction of the earth sciences with engineering and economics. This interaction is perhaps one of the reasons for the scarce information of what geothermal energy is, and how beneficial its uses can be. The general public is largely unaware, even now, of what geothermal energy is, or even of the meaning of the term 'geothermal'. Geologists, who know all about the Earth's heat and its possible uses, are in difficulty when tackling the technological side. On the other hand, engineers, who have the technology at their finger tips, have a poor knowledge of the Earth's interior.

It should be added that the energy experts that discuss renewable sources are normally engineers, physicists or economists, whose expertise is far from the earth sciences, and they are often unaware that our planet, besides the well-known fossil fuels, also conceals another resource of industrial significance such as geothermal energy.

A further reason for the lack of confidence in geothermal research amongst those working in the field of exact sciences is the uncertainty that accompanies anything that is concealed in the underground and has to be brought to the surface, especially if it is at depths of kilometres. Geologists call this uncertainty 'mining risk', sometimes high, often unpredictable. This risk is understandably not welcomed by engineers, economists and public officers, whose duty is to find a supply of energy from sources available with certainty and possibly stable in price and in time. Furthermore, weighing the scales even further against geothermal energy, is the fact that its exploitation requires expensive wells and surface installations such as pipes, heat exchangers, pumps, etc., which all prevents its use at a family level, as opposed to solar collectors, installed on the roofs of houses by the sea or in the mountains, or with small wind turbines so common in small farms. Exploitation of the geothermal

resource is, with few exceptions, an industrial activity requesting investments that are beyond the reach of a single family or even a small village.

Geothermal energy is not available everywhere, especially the resources needed for production of electric energy. However, this is not so big a drawback nowadays, when many countries have their own national grid, and electricity production can take place anywhere in the country. Unfortunately, however, not many regions are endowed with the necessary geological conditions for the production of geothermal electricity on an industrial scale. It will certainly be possible in the near future to locate new geothermal fields (hydrothermal), but the contribution of geothermal energy to the electric demand will never be significant in the industrialised countries. This is not true of developing countries where a significant percentage of their electric capacity could still be supplied from geothermal resources, in some cases more than 20% of the total electricity produced in the country.

Despite these drawbacks, it is a fact that the geothermal kWh is generally cost-competitive with conventional sources, and produced by means of well proven conventional technology. Geothermal energy is reliable, and indeed has been used to heat large municipal districts for more than 70 years, as well as to feed power plants of thousands of megawatts of electricity for more than a quarter of a century, and of hundreds of megawatts for more than half a century. The geothermal industry is now highly developed. Many companies are highly qualified for every aspect of development, from prospecting to plant financing. Nevertheless, excellent geothermal prospects remain undeveloped because developers and the financial community can still rely upon low fuel prices (but for how long?), and in this regard a new natural gas plant is also half as expensive as a new geothermal plant. The introduction of a pollution tax for the emission of CO_2 and sulfur, as recently discussed internationally, would significantly improve the environment and the economic competitiveness of geothermal resources with respect to fossil fuels (natural gas excluded).

The non-electrical uses of natural thermal waters, which can be found almost anywhere in the world, could certainly be expanded were governments to offer suitable, flexible and timely incentives. Furthermore, more information is needed on this source of energy, targeted at policy-makers, especially on a local level, and particularly as regards the environmental benefits attainable from this sustainable and benign form of energy.

At the moment, non-electrical geothermal applications are not particularly cheap compared to fossil fuels, but their convenience lies both in the possibility of saving conventional fuels for the high temperature uses (and oil for petrolchemistry), and in replacing with a national energy, machinery, and workforce imported fossil fuel, which has to be paid for in hard foreign currency [44].

15. Introduction to References

The following references are of outstanding interest: amongst *books*: Ref. [6] on geothermal reservoirs, Ref. [13], [51] and [55] on geochemical surveys, Ref. [52] analyses relations between volcanoes and geothermal reservoirs, Ref. [53] draws

together case studies from geothermal heating schemes in France, USA and Iceland, and Ref. [54] describes, in accessible terms, geothermal energy and its uses, electrical and non-electrical.

As for the *Proceedings of Conferences*, all sectors of geothermal energy exploration, utilisation, economics and environmental impact are widely discussed in the Proceedings of the World Geothermal Congress ‘95 (5 volumes, 535 papers, 3028 pages), and the Proceedings of the World Geothermal Congress 2000 (670 papers on CD Rom), cited above in section 13.2.2.

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